ELECTRICAL SUBSTATIONS

BY

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PREFACE

Reference to the Oxford Dictionary shows that the word "sub," when used to qualify a noun, is defined as "subordinate, secondary, under," and the title of this book, viz. *Electrical Substations*, may therefore give a false impression as to the importance of the subject.

The generating station is, of course, the source of all the electrical energy, but without the trunk mains which radiate from it, and the substations which these trunk mains serve, it would be quite useless.

The day of the generating station, which distributes direct to the consumer, is past, and the author feels quite confident in stating that within the next ten years practically the whole of the electrical supply in the world will be distributed to consumers through substations of one kind or another.

The passing of the Electricity Act of 1926 has drawn the attention of the public to the question of electrical supply, and "The Grid" is now a familiar term to most people who take an interest in the subject. "The Grid" consists of a network of extra high tension or super tension cables or overhead lines, which will eventually cover the whole of the country, and from this Grid every authorized distributor will take his electrical energy.

To convert this extra high tension or super tension current to a pressure suitable for the consumer, substations are absolutely necessary. The smaller and less economical generating stations will cease to generate and be turned into substations, and additional substations will be required in very large numbers.

From the above, it is clear that the electrical substation

is of considerable importance, and as very few books have been written on the subject the author hopes that this volume may be of some use to students, engineers, and those members of the public who take an interest in the development of electrical supply.

The book deals with the design and arrangement of the electrical substation itself, and the author has endeavoured to give a clear idea of the working of the various types of converting plant. It does not, however, profess to deal with the theory and design of converting plant, as this is too wide a subject, and has already been dealt with in several excellent books and publications, written by engineers who have specialized in this particular branch of electrical engineering.

The author ventures to think that the experience gained in twenty-seven years of electrical supply in the City of London may be of assistance to others. Several of the devices herein described are the outcome of this experience, and although they are generally quite simple they have at least the merit that they have been tried and found successful.

The question of manual versus automatic control of substations has been much debated, and although manually operated stations will still be necessary, the importance of the automatic station is so great that the author has devoted a considerable portion of this book to that branch of the subject.

The human element, the psychology of the switchboard attendant, the prevention of noise, are all important matters, and have been dealt with in the light of the author's own experience.

The maintenance of supply is as important, if not more so, than efficiency; and although provision for this purpose should not be carried to excess, some degree of sacrifice in efficiency is worth while to prevent consumers being thrown into complete darkness.

Finally, the author has endeavoured to give some idea of the present trend in electrical supply, and although, in view of the rapidity with which methods change nowa-

days, this is somewhat difficult, an attempt at prophecy is made.

The author wishes to express his indebtedness to the following for the information which they have placed at his disposal: The British Thomson-Houston Company, The Metropolitan Vickers Electrical Company, Reyrolle & Company, The British Electric Transformer Company, The British Brown Boveri Company, Power Rectifiers, Ltd., Bertram Thomas, The Tudor Accumulator Company, The Automatic Telephone Manufacturing Company.

Special thanks are also due to Professor Ernest Wilson, King's College, London, Mr. L. C. Benton of the Metropolitan Vickers Co., Messrs. Cutbush and Kemsley of the City of London Electric Lighting Company, and several others, whose names are duly acknowledged in the book.

H. Brazil

London

June, 1928

CONTENTS

CHAPTER I

SYSTEMS OF SUPPLY

L.T. Distribution Systems. To plan a city distribution system is not an easy matter, as one has to provide not only for the load that will first have to be supplied, but also for the future when the load may be quadrupled.

In laying low-tension mains in a large town, the cost of excavation and labour is such a large proportion of the total cost, that it pays to put in mains of ample section and to allow for future loads. If this is done, although a large amount of money will have to be expended on the mains themselves, it will obviate a very expensive extension when the load increases, and also the copper losses will be materially reduced.

Planning for the Future. Messrs. Beard & Haldane [1] advocate looking ahead fifteen years, and, on the basis of an annual increase of the load of 15 per cent., suggest putting in sufficient cables to deal with the load fifteen years hence. This does not mean that this load is to be supplied from the same substations as were installed at the beginning of the scheme; this would clearly be impossible. Their scheme is to lay out the network in such a way that, by introducing other substations in distributing centres at various points in the network, it may be capable of dealing with three or four times the original load. They assume that all new low-tension systems laid out in the future will be of the alternating current, three-phase, four-wire type, 400/230 volts, 400-volt three-phase for power, and 230-volt single-phase for

[1] Paper read before the Institution of Electrical Engineers, November 4, 1926.

lighting; and although the author is not prepared to agree that all future systems will be of this type, the arguments they put forward apply equally to direct-current systems with automatic substations instead of transforming static substations.

Lay Out of L.T. Mains. The lay out of the L.T. Mains is shown in Fig. 1, and there are three stages illustrated. The first is that required for the first five years, all the current being supplied from one substation in the centre of the area. For the second period of five years, two other substations are added, and the effect of this is to reduce very greatly the distance over which supply has to be given.

For the third and final period, six more substations

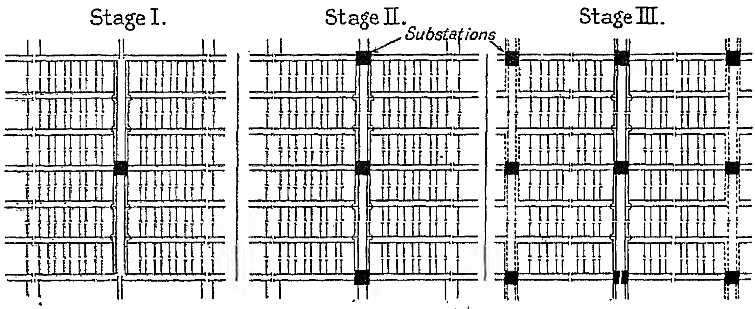

FIG. 1.—Messrs. Beard & Haldane's Scheme for an A.C. Low-Tension Mains System, showing how the Increase in Load is dealt with by adding Substations.

are added, and it is also necessary to lay some additional mains on the outskirts of the area. In practice, of course, any city—at any rate in this country—will not have its streets laid out as shown in the sketch, nor is it likely that substations or distributing centres can be installed at the exact points indicated, but the principle is correct, and sufficiently near approximations can be made to it in practice to render the advantages very real.

It will be noted that the network shown is what may be described as the distributor type, *i.e.* service connections are made off the cables which radiate from the substation, but the author is not prepared to agree that this type is

the best in practice. Messrs. Beard & Haldane have assumed that all the distributing centres are of the same capacity, and while this may be the best arrangement where alternating current is employed and where the load is reasonably uniform, it would not be suitable where very heavy loads have to be dealt with, and when the system of supply is direct current.

D.C. Substations still required. In the author's opinion there will still be a considerable demand for continuous current in the future, especially in large towns, for printing work. At the present time, newspaper proprietors, and other large users of printing machinery, insist on D.C., and nearly all the large plant used is designed for continuous current. Unless, therefore, it is considered desirable to have two systems of mains throughout the town, one D.C. and the other A.C.—and this would not be economical from a mains point of view—provision must be made for supplying from substations, converting from E.H.T. to D.C. in those parts of the district where the printing load exists.

Planning Number and Positions of Substations. Discussing for a moment a town where the load is very dense over an area of, say, 2 square miles, it would appear to be necessary to instal straight away three or four main substations, and to lay out the mains so that these main stations could supply the whole load for the greater part of the twenty-four hours, and would only need assisting in the case of darkness, or over the ordinary peak load. This assistance would be given by automatic substations placed at points in the area where this assistance would be of most value (see Fig. 2). These automatic substations would not be installed immediately, but only as and when required. They should be completely automatic as far as starting up is concerned, but should be remotely controlled from the main stations. The extent of this remote control is a matter which has to be decided on its merits in each case, but it should be possible to start up and shut down the automatic substation, and to open and reclose the feeders that radiate from it.

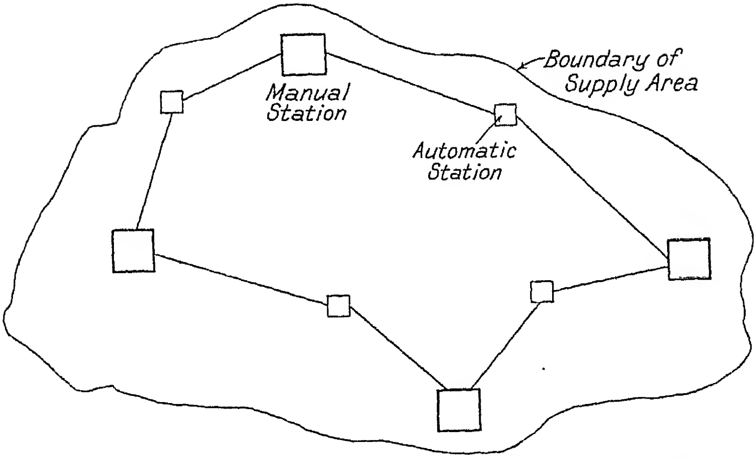

Fig. 2.—Diagram to illustrate how the Increase of Load is dealt with by Automatic Stations.

Distribution by Feeder or Distributor System. The decision as to the system of mains radiating from the substation is of very great importance. Messrs. Beard & Haldane suggest that the distributor system is the best. This may be the case where alternating current is used, and the distributing centres are so numerous that the difference between the busbar pressure and the pressure on consumers' terminals is very small, but in the early stages of an undertaking it will not be possible to have so many of these distributing centres, and the voltage drop will be much greater. This means that the consumer close to the station gets practically busbar volts, and the consumer midway between two distributing points gets considerably less.

Combined Feeder and Distributor System. The author is of the opinion that there are many advantages in the feeder system, and he has for some time past been using, with gratifying success, a system which combines to some extent the two systems. This system is illustrated in Fig. 3.

The mains were originally laid out purely as a feeder system, but the distributors from the shorter feeders

radiate back towards the substation in order to pick up the load. Several of these distributors are taken right into the substation, and until quite recently they have only been used to supply the need of the substations for lighting, etc.

Now these short feeders, as is well known, tend to take up a heavy load and feed into the other feeder areas, and

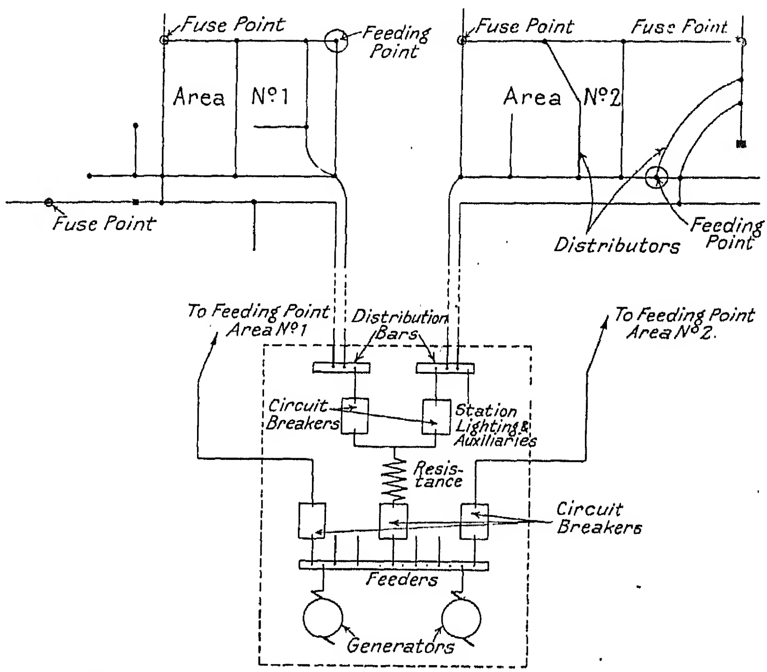

FIG. 3.—Diagram to illustrate the Combined Feeder and Distributor System with "Resistance Feeder."

they very soon become overloaded. One method of overcoming this difficulty is of course to duplicate the feeder, but this is expensive. Another method of preventing this overload is to instal a resistance in these short feeders, and this, although at first sight it may appear a retrograde step, is quite justifiable in certain circumstances. It, however, tends to increase the busbar volts, and a better solution is that shown in Fig. 3.

The three or four distributors which enter the station are connected to a common busbar through circuit-breakers. This busbar is fed by a short cable from the main busbars through a heavy current resistance which is adjustable. The circuit-breakers are set for instantaneous action (high-speed breakers would be preferable), and when a fault comes on any feeder area, this area is cut away from the other areas at once by the action of the circuit-breaker, and thus the fault does not affect the other areas. The beneficial effect of this arrangement is very marked, and by altering the value of the resistance, the amount of current sent down these resistance feeders can be regulated. In effect, the installing of these resistance feeders is equivalent to the putting in of several new feeders at merely the cost of the circuit-breaker and resistance.

Another advantage is that there are two feeds to these feeder areas, which is invaluable when splitting up a feeder area for earth testing.

CHAPTER II

DESIGN OF SUBSTATIONS

Having now considered the method of distribution and the number of substations required, let us consider the substation itself. A manually controlled station in a large town, in which is installed a considerable number of machines will be dealt with.

Means of Access. If possible, the station should be on the ground floor, so that the plant can be picked off the lorry and deposited in its place with the minimum risk and loss of time. Unfortunately this is not easily arranged, and in many cases resort has to be had to a basement or to railway arches. The latter alternative should be avoided if possible, as the restrictions imposed by the railway companies on the cutting of holes in the building make the cabling of the machines a very difficult operation. If a basement has to be used, great care should be taken to see that the access to the hatchway down which the plant has to be lowered is easy, and that the hatchway itself is of ample dimensions.

Ventilation. The question of ventilation is sometimes difficult, but it can be overcome. After many years of experimenting, the author is of the opinion that it is of very little use to rely on exhaust fans, and hope that the cool fresh air will find its way into the station to replace that which has been driven out; but that the proper way is to instal fans which force air into the station, care being taken that the inlet side of the fan is connected by a trunk to a source of cool fresh air. This point is of importance, not only from the point of view of the comfort

of the attendants, but also because it keeps down the temperature of the machines.

Another point of great importance in the selection of a site for a substation is that it should be so placed that the low tension feeders which radiate from it can be taken out at two or more independent points so as to avoid the dangerous bottle-neck arrangement that unfortunately is far too common.

Relative Position of Machines and Switchboards. The next thing to be considered is the relative positions of the E.H.T. switchgear, the L.T. switchgear, the machines and the L.T. busbars at which the feeders terminate. It is astonishing what a large amount of power is wasted in many substations owing to the unsuitable arrangement of the above-mentioned gear. The first thing to do is to get the L.T. side of the machines as near as possible to the L.T. busbars from which the feeders radiate. The second is to get the L.T. switchgear and circuit-breakers close to the machine and, if possible, in the line between the machine and the L.T. busbars. In many cases it is not possible or convenient to arrange the control panel in this line, in which case it is better to split the gear into two panels, the one containing the L.T. switches and circuit-breakers being as near the machine as possible, and the other containing the regulating switch, instruments, etc., in a convenient position for the operator to work. Push-buttons on this board will control the opening of the E.H.T. switch and L.T. circuit-breakers. With this arrangement, the length of the L.T. connection between machine and L.T. busbars is kept down to a minimum, and therefore the C^2R losses are a minimum also.

The E.H.T. panel and switch can be placed some distance from the machines if necessary, as the C^2R losses in the E.H.T. cable are practically negligible.

C^2R Losses in Cable Connections. The difference between the losses in the E.H.T. and the L.T. side of a converter is not generally appreciated, and an example from actual practice may illustrate the point. Take the case of a 1.500 kW. machine converting from 10,000-V.

I^2R

three-phase to 200 volts D.C. Assume a length of run in each case of 120 feet. Now at full load the E.H.T. current will be 83 amps in each phase, and the C^2R loss will be about 300 watts. The L.T. current would be 7,800 amps, and the C^2R loss 18,700 watts.

Plug Board Connections. Another point of importance is to arrange the L.T. busbars in two or three sections, so that a machine or machines can be isolated on to certain groups of feeders. This is of great use in earth testing, and renders it possible to keep the whole of the consumers going, although there may be a negative earth on one part of the area and a positive earth on another part. These two earths in an undivided area would cause a short circuit, and a number of consumers would certainly be cut off.

Design for a Large Substation

Fig. 4 illustrates an economical design of a substation such as is required in a large town. The capacity of the substation at normal full load is 17,000 kW., each machine having an overload rating of 25 per cent. for two hours, or 50 per cent. for fifteen minutes.

Type of Plant. The type of machine that the author favours is the motor converter, and there are five of these, each for a normal full load of 2,500 kW. There are also three rotary converters, normal full load 1,500 kW. All the above machines are arranged with a middle wire connection.

The rotaries are supplied from single-phase transformers and one spare transformer is kept in the station. A breakdown on one of these transformers need not keep the rotary out of commission for more than about two hours, as the spare one can be wheeled into place and connected up within this time.

E.H.T. Connections. The 11,000-volt feeders are brought in at one corner, and are controlled by ironclad oil-immersed circuit-breakers. In the same line with these switches is placed a series of stone cubicles, one for each

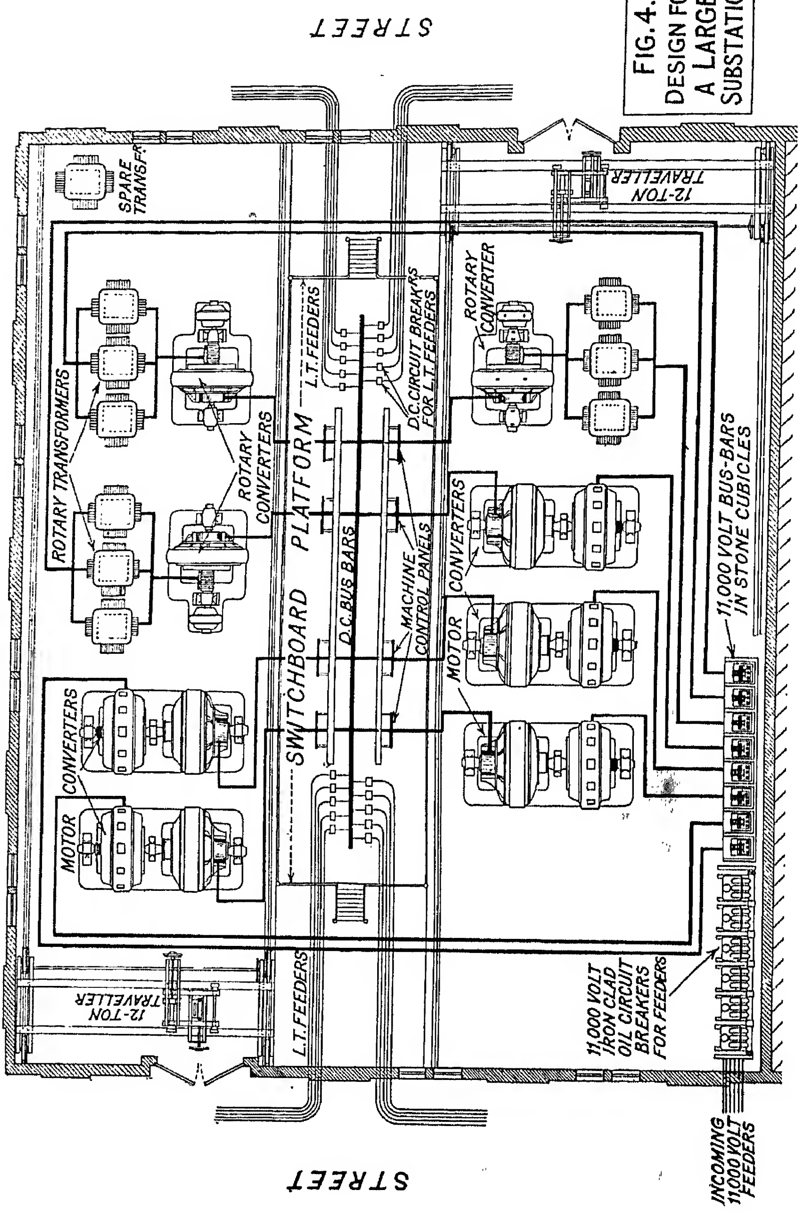

FIG. 4. DESIGN FOR A LARGE SUBSTATION

machine. In these cubicles are mounted air-break single-pole link switches, operated by a metal hook mounted at the end of an insulated rod. Each switch is separated from its neighbour by an insulating partition. The doors in front of these cubicles are covered in with stout wired glass.

These isolating switches enable one to completely disconnect any machine at will, and furthermore the switchboard attendant can satisfy himself by looking through the glass window that any machine which he wishes to clean or work upon is entirely isolated. In some cases, as an additional precaution, the isolating switches are so made that, when they are pulled out, they fall into other contacts which are connected to earth. When all three switches are out, the machine is isolated, short-circuited and earthed. Below the isolating switches are mounted the oil switches controlling the machines, and these are tripped by push-buttons on the machine control boards.

The author recommends the cubicle system for the machine busbars, because, although they are not so safe as the ironclad arrangement, they are very much cheaper and more flexible, and enable the single-core cables which run from them to the machines to be connected easily and with little expense.

Single-Core or Three-Core Cables for Machine Connections. The use of single-core lead-sheathed cables for machine connection has given rise to much discussion, some engineers arguing that the sheath losses are so considerable that it is not good practice to employ them. The author has used single-core lead-sheathed cables of 0·75 sq. inch and 1·0 sq. inch for machine connection, and contends that, if suitable care is taken, the sheath losses are negligible.

By using single-core cables, the possibility of shorts between phases is eliminated, and the flexibility of the cables is very much greater than is the case with three-core, enabling difficult corners to be negotiated without any risk.

If possible the three cables to any one machine should be grouped in the clover leaf or triangular formation (see Fig. 5), and this will almost entirely eliminate the sheath losses. The cables should not be run near iron, nor be supported by iron cleats, and of course they must not be armoured.

The best type of single-core cable for machine connection is the cambric type, in which the whole insulation round the core is made up of varnished cambric. There is no oil in this cable, and quite long vertical runs can be

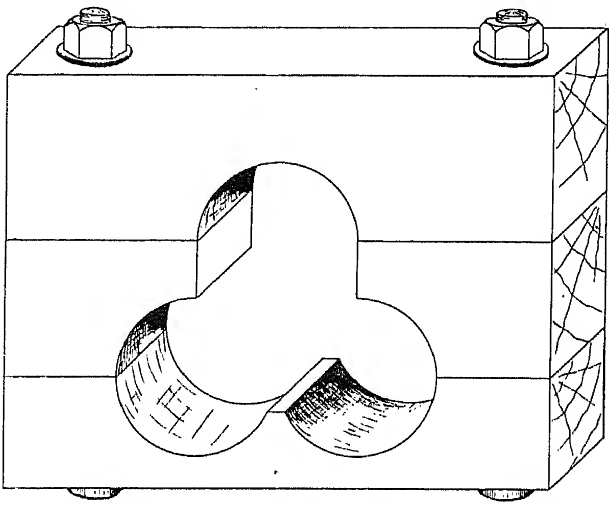

FIG. 5.—Clover-leaf Cleat for assembling three Single-core Lead-sheathed Cables.

made without any trouble from oil bleeding, which is generally the case with oil-paper insulated cable.

Wherever possible, trenches should be run from the oil switches controlling the machines to the stator in the case of motor converters, and to the transformer in the case of rotary converters. If the clover-leaf formation is adhered to, in this trench iron chequer plates can be used on the top of the trench without any bad results. When using lead-sheathed single-core cables, where it is not possible to group them in the clover-leaf formation, the leads of the cables must be connected together and to earth at

one point only. The object of this is to prevent the currents circulating along the lead sheaths.

In the case of single-core cables, where it is necessary to make a plumbed joint at each end of the cable, the metal box at one end into which the lead of the cable is plumbed and which is normally bolted direct on to the iron case of the switch or transformer and there is connected to earth, must be insulated from the iron case by bushing the bolts, and inserting insulating material between the joints of the box.

There is an alternative to this method, and that is to tape the lead of the cable, or insulate with a bush, where

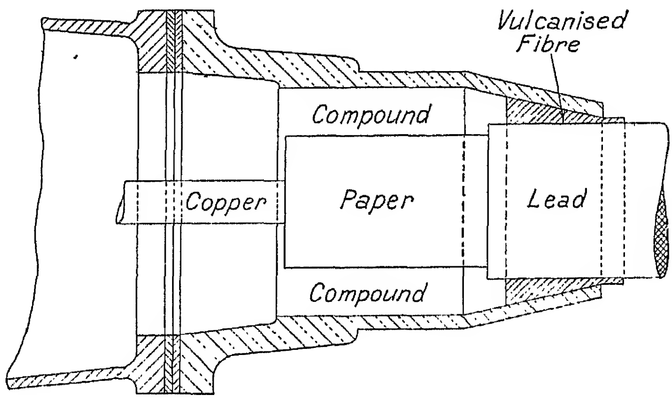

FIG. 6.—Sheath Bushing for E.H.T. Terminal Bell.

it enters the box, and in this case, of course, the box need not be insulated from the iron case. This method is illustrated in Fig. 6.

C^2R Losses reduced to a Minimum. The chief thing to notice about the design of this substation (see Fig. 4) is that the C^2R losses are reduced to a minimum. As already explained, the length of the 11,000-volt leads is not of great importance, as the current in them being relatively small, the C^2R losses are also small.

It will be noted, however, that the L.T. D.C. side of the machines in which the heavy currents have to be dealt with are as near to their control panels as can be

arranged, and the D.C. main busbars run right down the centre of the operating platform immediately behind the machine control panels. By this arrangement the C^2R losses, and the cost of the cable or copper strip between the machine and control panel, and between panel and D.C. busbars, is reduced to the minimum. The L.T. feeders are brought in at opposite ends of the station and connected to the ends of the main D.C. busbars. Of course it is not always possible to obtain a site for a substation where this can be done, but it is a very desirable arrangement, as it prevents congestion of the feeders, and also reduces the C^2R losses in the main busbars. It is of course impossible to show all three wires on the A.C. and D.C. side, and the thick line merely indicates the way in which the plant is connected together.

The three-phase 10,000-volt current passes from the E.H.T. feeder busbars to the machine busbars, thence through the isolating switches and the oil switch to the stator (in the case of motor converters) and the transformer (in the case of rotary converters). The secondary L.T. alternating current then passes into the rotary or the D.C. end of motor converter, and emerges as direct current. It is lead to the machine control panel through suitable main switches and circuit-breakers, and then passes on to the main D.C. busbars, from whence it flows through the circuit-breakers to the feeders, the distributors, and the consumer.

The current from the D.C. side of the motor converters, assuming a 400-volt supply, is about 9,000 amps. (overload), and the connections from machine to panel and panel to the busbars become troublesome if cable is used. The best arrangement is to use wide copper strip insulated with presspahn and empire cloth to a thickness of about three-eighths of an inch.

It will be noted that in the design illustrated in Fig. 4 two entrances are shown with an overhead traveller in each bay. This arrangement is very desirable, as it facilitates erection and dismantling, and does away with the necessity of shifting plant from one bay to the other.

CHAPTER III

STATIC TRANSFORMER SUBSTATIONS

In this type of substation there is no rotating plant, the reduction of pressure from the three-phase E.H.T. to a suitable pressure for use in consumers' premises being done by static transformers.

Types of Transformer. There are two main groups: (1) Shell, (2) Core.

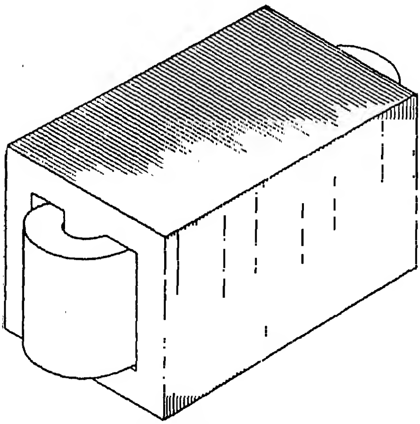

Fig. 7.—Shell Type Transformer.

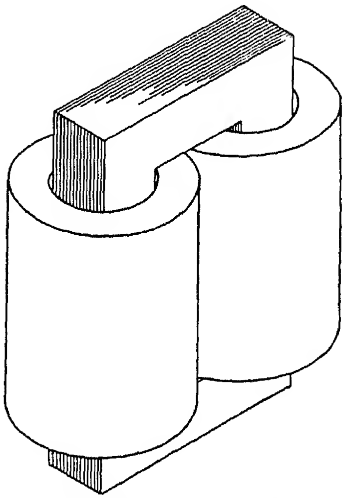

Fig. 8.—Core Type Transformer.

A typical shell transformer is shown in Fig. 7, and a core transformer in Fig. 8 (Kapp's Transformer).

Shell Type. In the case of the shell transformer, the primary is wound on top of the secondary, the coil being of an oblong shape, and, with the exception of the ends,

is surrounded by iron. In a variety of this design introduced by Mr. Berry and used very extensively, the coils

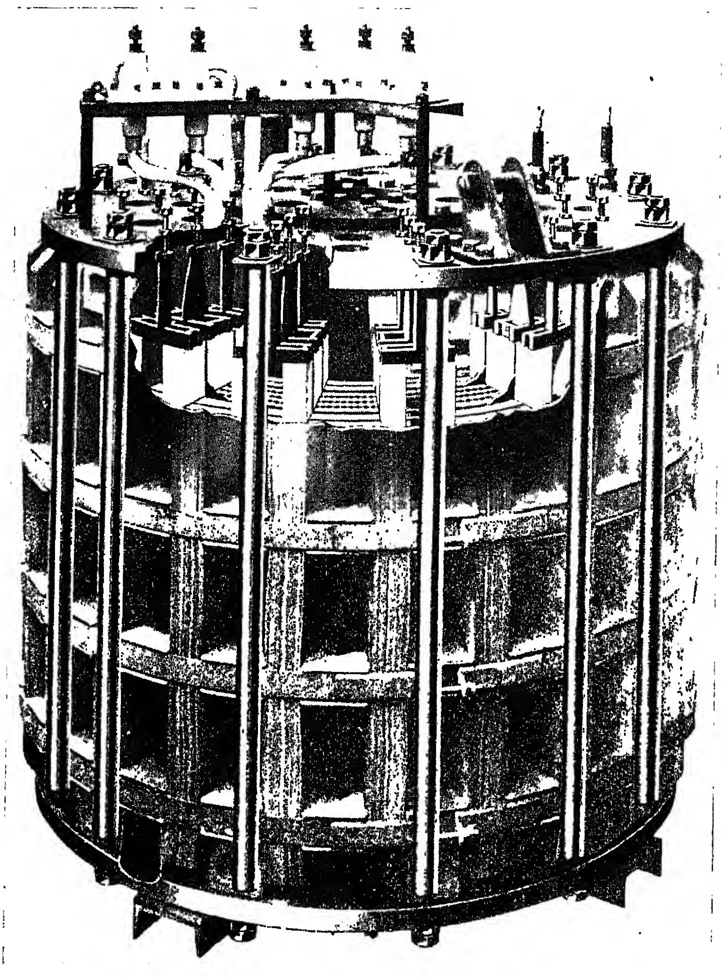

FIG. 9.—Phantom Picture of Berry Transformer, Dreadnought Pattern.

are circular, and the iron stampings are arranged in sections all round the circle, as shown in Fig. 9. The advantage of this arrangement is that a large surface of

when the two arrows are pointing in opposite directions, the potential in the secondary of T_2 is subtracted from the line, and when they point in the same direction, this potential is added to the line.

Fig. 11 shows the maximum positive boost. In this case the whole of the windings of the auxiliary transformers are in use, and the potential in the secondary of T_2 is added to the line. Fig. 12 shows the maximum negative boost, and here the full potential of the secondary T_2 is subtracted from the line, this being accomplished

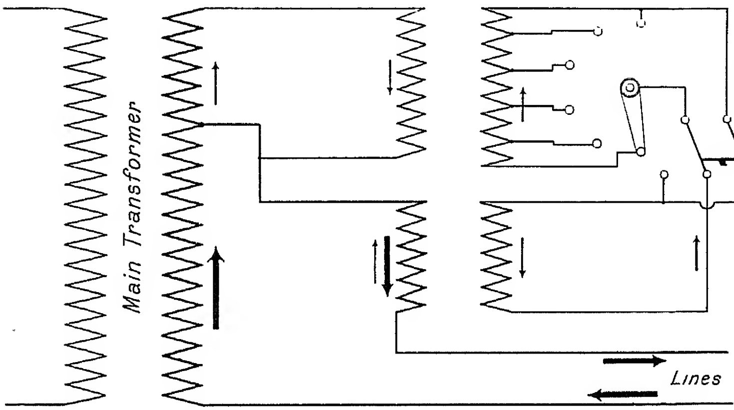

FIG. 12.—The Berry Regulator. Boosting to give minimum volts on supply.

by reversing the connection between secondary of T_1 and primary of T_2. Fig. 13 shows the arrangement with no boost at all. In this case it is necessary to open circuit the secondary of T_1, and short circuit the primary of T_2, so as to render the secondary of T_2 non-inductive, the only losses in this coil then being due to ohmic resistance of the copper.

In the foregoing, reference has been made to single-phase only. For three-phase, three single-phase sets mechanically coupled are required.

Induction Regulators. Another type of boosting apparatus is the Induction Regulator. This may be looked upon as a shell type transformer, in which the

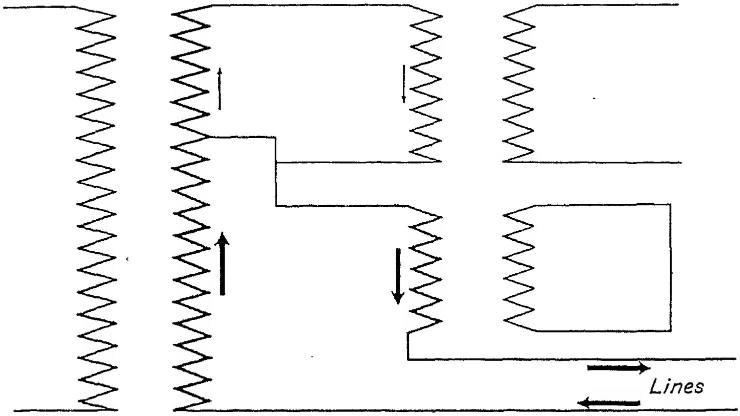

FIG. 13.—The Berry Regulator. No Boost.

primary and secondary windings can be rotated relatively to each other (see Fig. 14). The primary is connected across the line, and the secondary in series with the line. If the secondary is in the same relative position

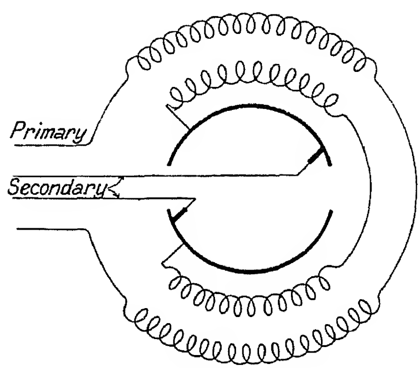

FIG. 14.—Induction Regulator.

to the primary as is the case in an ordinary transformer, *i.e.* practically the whole of the lines of force produced by the primary pass through the secondary, then we have the position of maximum positive boost of the line volts. If we rotate the secondary through 180°, we still

have the same relative position of primary and secondary, and consequently the voltage produced in the secondary is the maximum as before. The direction, however, of the voltage in the secondary is reversed, and it therefore subtracts from the line voltage, giving the position of maximum negative boost. If the secondary is rotated through 90°, the lines of force produced by the primary do not pass through the secondary, and therefore no voltage is produced in it, this being the position of no boost. It is obvious, therefore, that by rotating the secondary through 180° we can get an infinite number of voltages from maximum positive boost through zero to maximum negative boost.

It will be noticed that the secondary has to carry the whole of the current in the feeder which is being regulated, and the Induction Regulator is therefore a somewhat bulky and expensive piece of apparatus, and furthermore it reduces the efficiency of the system.

Parallel Circuit Method of Regulation. Standard power transformers are generally fitted with tappings having a range of the order of 2½ and 5 per cent. These are usually placed on the high voltage side, and it is now frequently specified that these tappings shall be taken to a tapping switch which can be operated from outside the tank. This is to enable tappings to be changed more easily without having to remove the tank cover, or to unbolt any link connections. The advantage of this is found particularly in the case of transformers fitted with oil conservators. Tapping switches have been developed to meet this demand, but are not suitable for interrupting current, and must be operated with the transformer dead; or with ordinary double-wound transformers, the switches can be operated with the transformer on open circuit, if they are arranged on the secondary side.

In order to get over this difficulty of regulation while on load, a method which is called the "Parallel Circuit Method of Regulation" has been developed, and the author is indebted to the Metropolitan Vickers Co. for

the description of the apparatus made by them to achieve this end. The diagram of the connections is shown in Fig. 15.

The scheme is only possible if the main transformer and the regulating gear are being built at the same time. One winding (either the H.T. or the L.T., as is most convenient) is arranged in two circuits, which are normally

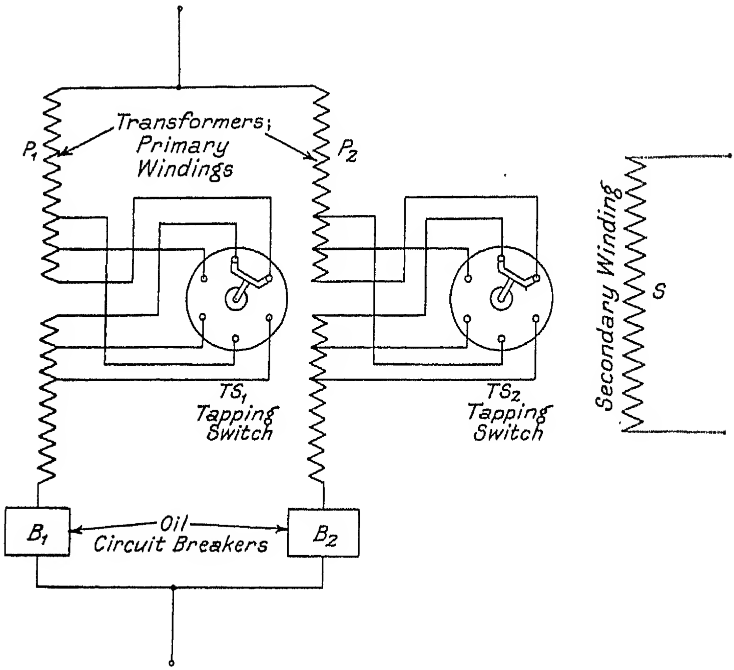

FIG. 15.—Parallel Circuit Method of A.C. Regulation.

connected in parallel, and each is designed to carry normally one-half of the load current.

A number of duplicate tappings is fitted to each parallel circuit, and carried to two separate open circuit type standard transformer tapping switches, placed inside the tank and operated through spindles passing through oil-tight packing glands in the tank side. In each parallel circuit an externally mounted oil circuit-breaker is included. With this arrangement of circuits it is possible

to change the tapping switches without interrupting the load :

The opening of one circuit-breaker transfers the whole load temporarily on to one winding. This enables the tapping switch of the open-circuited half-winding to be changed to the next tapping position, and the circuit-breaker can then be closed again. The transformer is then working temporarily with the two half-windings having unequal number of turns, and current will circulate between the two circuits. The magnitude of this circulating current can be kept within safe limits by suitably proportioning the reactance between the two parallel windings.

The second circuit-breaker can then be opened, thus transferring the whole load temporarily on to the first half-winding. The second tapping switch can be moved to the same position as the first one, and the second circuit-breaker closed again. This completes the operation of changing the transformer on both windings from one tapping to the next.

In order to avoid sudden fluctuations in voltage during the process of tap changing, considerable care has to be taken in the design of the windings. The arrangement to be aimed at would be for the reactance between each of the windings P_1 or P_2 to the other winding S to be equal, and also for the reactance of either of them to the other winding S to be as nearly as possible equal to that of the two windings (when connected in parallel) to the other winding S. If this condition is satisfied, there will be no large increase in reactive drop when the whole of the load is thrown temporarily on to one half winding. The reactance between the half-windings P_1 and P_2 should be fairly high, in order to keep down the circulating current when running on unequal tappings on the two halves. It is not possible to design to meet all these ideal conditions exactly, and a compromise has to be effected, which, however, gives a satisfactory arrangement without any objectionable voltage fluctuations when tappings are changed.

The tapping switch spindles and the circuit-breakers can only be operated in the correct sequence, as they are coupled by means of a mechanical sequence device. The latter is so arranged that one turn of its driving shaft carries through the operations of (*a*) opening No. 1 circuit-breaker, (*b*) changing No. 1 tapping switch, (*c*) closing No. 1 circuit-breaker, (*d*) opening No. 2 circuit-breaker, (*e*) changing No. 2 tapping switch, and (*f*) closing No. 2 circuit-breaker.

The circuit-breakers are actuated through steel cams. It should be noted that standard types of transformer tapping switches and oil circuit-breakers are used, and the only new apparatus required is the mechanical sequence device. In addition, the circuit-breakers have a very much lighter duty to perform than under the normal conditions for which they are used.

In the open position, the voltage across the break is only equal to the impedance voltage drop of the transformer windings. The circuit-breakers only serve to transfer the load and do not have to break circuit. The sequence device and oil circuit-breakers are mounted on a bracket attached to the transformer tank, as shown in Fig. 16. The mechanism may be hand-operated or arranged for motor drive and controlled by push-button or for fully automatic control.

The motor drive is also a standard piece of apparatus, and when arranged for this, provision is also made for hand operation by a crank, in case of failure of the motor or control gear. When the motor-operated gear is once set in motion, it is out of the control of the operator or the operating gear, until one complete cycle of changing of tappings has been completed, so that it is not possible for the operator to leave the mechanism in an intermediate position. This is achieved by cam-operated pilot switches (actuated from a cam-shaft driven by the motor), which open the motor circuit and stop the motor at the appropriate time. Limit switches, which open the motor circuit when the end positions of the range of tappings have been reached, prevent travel of the mechanism

beyond the extreme positions. Mechanical stops are also provided for the same purpose, as an additional safeguard.

To guard against possible failure of the motor leaving the transformer on unequal tappings, or with only one half-winding in circuit, a current transformer is included

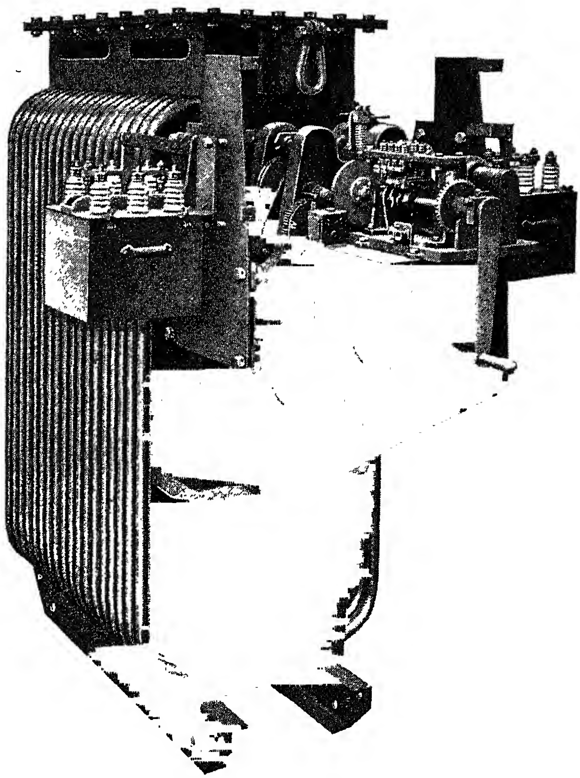

FIG. 16.—Three-phase Transformer Tank and Switch Operating Gear for "Parallel Circuit" Method.

(Connections to Switches and Guards not shown.)

in each parallel circuit. These are used in conjunction with a protective relay which functions when there is an out-of-balance current existing between the two half-windings for longer than a predetermined time. There will, of course, be no out-of-balance current when the

two half-windings are in circuit on equal tappings. It will be seen that adequate provision has been made for protective devices, and a position indicator shows the

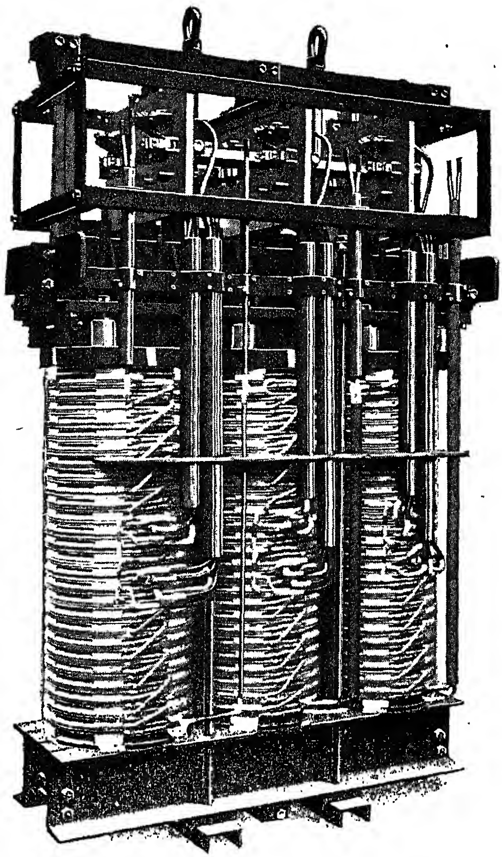

FIG. 17.—Three-phase Transformer, with Tapping Switches, arranged for "Parallel Circuit" Method.

tapping position on which the transformer is being operated.

The illustrations show a 500 kVA. three-phase, 50-period 6,000/400-volt delta/star-connected transformer, arranged for this system of control. Fig. 17 shows the transformer

and tapping switches, and Fig. 16 shows the complete external assembly.

In the case where automatic motor control is employed, a number of tappings have been provided on the H.T. side between the limits 6,000–5,500 volts, and it is arranged that the voltage on the L.T. side shall be maintained fully automatically at 400 V. with variation of the supply voltage on the H.T. side between these limits. This system can of course also be applied to transformers of very much greater kVA. capacity than that of the example illustrated.

The same apparatus can be used for a 2,500 kVA. single-phase, or a 7,500 kVA. three-phase transformer at 6,600 volts. With an alternative circuit-breaker, it can be extended to deal with a 4,000 kVA. single-phase or 12,000 kVA. three-phase transformer at 11,000 volts. With a further alternative circuit-breaker, the limits can be extended to a 12,000 kVA. single-phase, or a 36,000 kVA. three-phase transformer at 33,000 volts.

Low Tension Single-Phase Distribution of the City of London Electric Lighting Co. By the courtesy of Mr. Frank Bailey, the author is enabled to give a description of the way in which the problem of adapting an existing single-phase system to modern requirements was solved. The original system of the City of London Co. was single-phase A.C., generation being at 2,200 volts, 100 periods, at Bankside, the current being sent to various transformer stations, and transformed down and distributed on the 110, 220 volts, three-wire system.

As more generating plant became necessary at Bankside, extensions took the form of three-phase, 50-period, 11,000-volt sets, so as to conform to the standard which has been adopted in this country, and a scheme had to be devised to supply the old 2,200-volt single-phase system from the new one. The transformer stations were therefore first equipped with larger 50-period transformers instead of the 100-period, and at the same time the network voltage was increased to 220, 440, three-wire. These 2,200 to 220 and 440 volts transformer stations

were also arranged in three groups, the maximum demand on each group being approximately the same.

A large substation at Aldersgate Street containing twelve 1,500 kVA. single-phase transformers was then put down, and equipped to supply these 2,200-V. stations. The twelve transformers are arranged in four groups of three each, transforming down from each phase of the 11,000 volts system, to three separate 2,200-volt switchboards, from each of which cables radiate to the groups

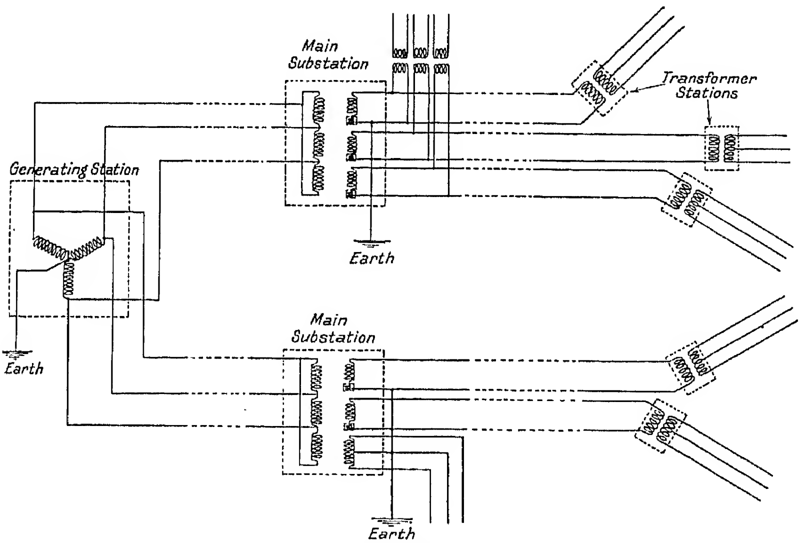

FIG. 18.—Low-Tension Single-phase Distribution of the City of London Electric Lighting Co.

of transformer stations mentioned above. These transformers are arranged with $2\frac{1}{2}$ per cent. tappings on the E.H.T. side, and the 2,200-volt side is further equipped with Berry regulating switches, by means of which the voltage can be altered on load in steps of $\frac{1}{2}$ per cent. over a total range of 5 per cent.

In order to supply current in the vicinity, three smaller 2,200-volt switchboards were erected, one on each phase, and these supply three groups of transformers, ratio 2,200 to 215 and 430 volts, which provide current for

the local three-wire network for lighting, heating and cooking. It will be observed that the current for the 215 and 430-volt distribution system has to be transformed

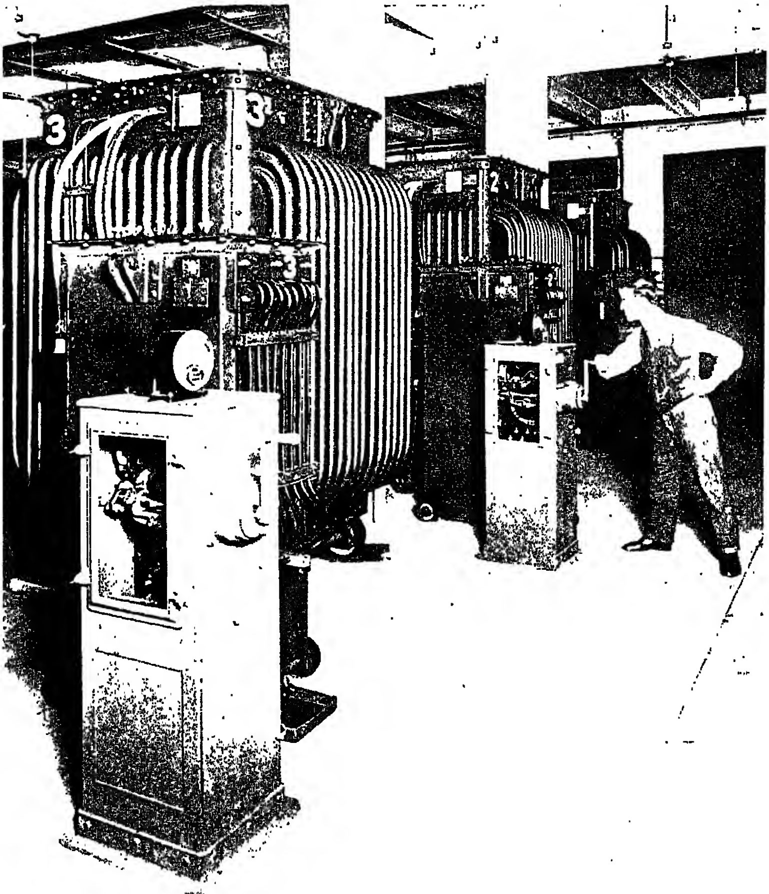

Fig. 19.—City of London Co.'s Aldersgate Substation, containing twelve 1,500 kVA. Single-phase Transformers with Berry Regulators.

twice, this being unavoidable owing to the existing system having to be fed from the new one.

In a newer substation, which has been in operation about eighteen months, transformers have been installed.

IISc Lib B'lore
621.3126 N28
3464
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in which one-phase is arranged to transform from 11,000 to 215 and 430 volts, the other two phases converting from 11,000 to 2,200, as in the other substation.

Fig. 18, which shows one set of three single-phase transformers in each of the large substations, and one single-phase transformer in the transformer stations, should explain the system. From the above explanation, it is clear that single-phase L.T. distribution is still retained, although the generating sets are three-phase.

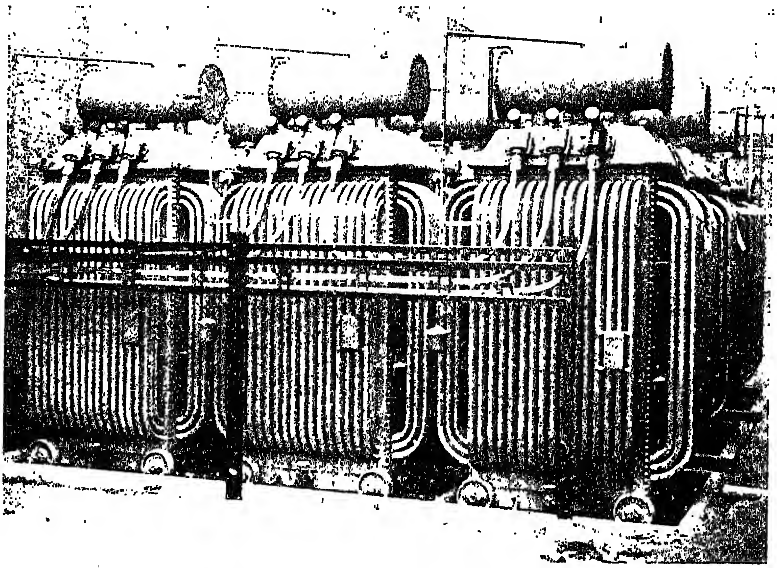


FIG. 20.—Group of Outdoor Transformers, 24,000 kVA. with Conservators.

For large bulk supplies, the three-phase 11,000-volt mains will be taken into the consumer's premises, and transformed down, so that three-phase motors can be employed if it is thought desirable.

Fig. 19 shows one group of three 1,500 kVA. transformers in the Aldersgate substation, to which reference has already been made. The view shows a man regulating on the Berry Regulator, description of which is given elsewhere (p. 18). Fig. 20 is a picture of a group of Outdoor Transformers, 24,000 kVA., fitted with con-

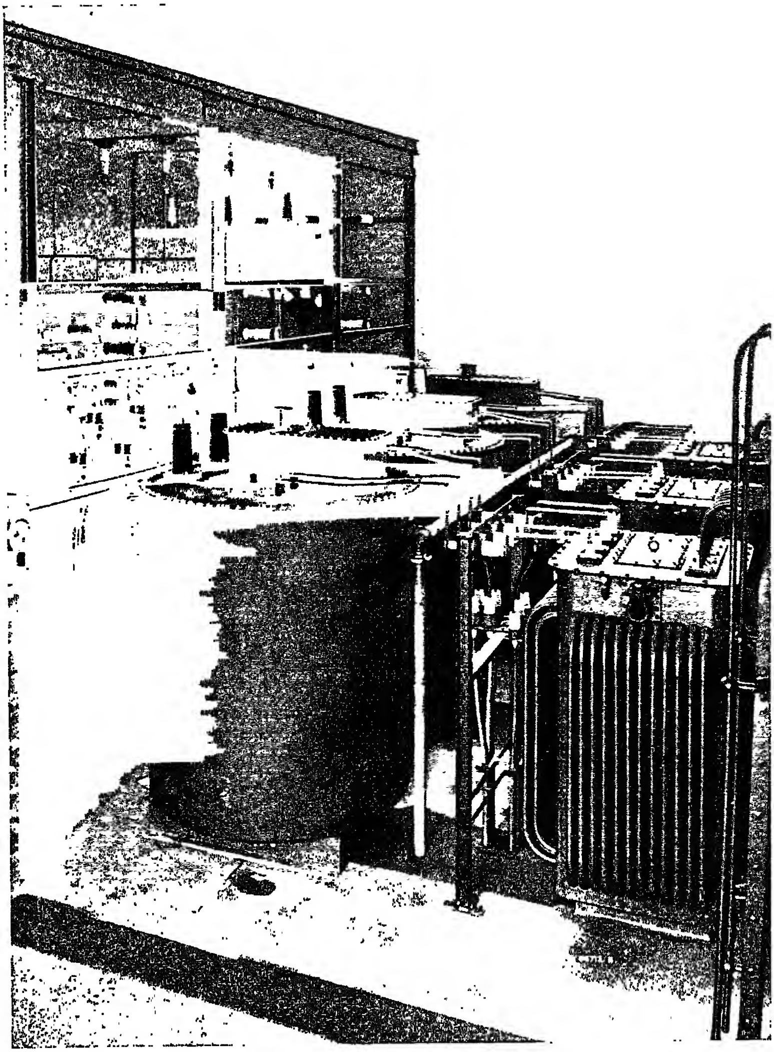


FIG. 21.—Group of Indoor Transformers, 18,000 kVA. with Regulators.

servators for maintaining the level of oil above the transformer windings. Fig. 21 shows a group of Indoor Transformers, capacity 18,000 kVA., with regulators alongside.

CHAPTER IV

E.H.T. BUSBARS AND SWITCHGEAR

The design of the E.H.T. busbars and switchgear is a matter of very great importance in a substation, as a short circuit on the busbars, or a failure to break circuit on a switch, may be disastrous to the plant, and also possibly to the attendants. The amount of power behind a short circuit in these days of 60,000 and 90,000 kW. sets is enormous, and under certain circumstances the switchgear in the substation will have to rupture the circuit.

The author's experience over a period of twenty-five years, with different types of busbars and switches, may be of interest, as it illustrates the line along which progress has been made.

Development of E.H.T. Busbars. Twenty-five years ago, the amount of current sent out from any substation in this country was a mere fraction of that which is required to-day. Generating sets were small in capacity, as were also the E.H.T. mains and the converting plant in the substations. For example, generating sets of 2,000 kW., mains of 0·1 sq. inch section, and converting sets of 350 kW., were quite usual. Under these conditions it can easily be understood that the current which flowed when a short circuit occurred, particularly if an arc was formed, was not great. No balanced protective devices were available for cutting out the feeders in those days, and the fault had to be cleared by the overload coil. The author has seen an arc playing between the bare copper busbars for some time, the current not being sufficient to trip the circuit-breaker on the feeder, and

eventually the arc had to be extinguished by mechanically interrupting it.

The busbars at that time on a 10,000-volt three-phase system were bare copper strips about 5 inches apart supported on porcelain insulators, which were fixed to an unprotected angle-iron structure. The busbars were placed behind a metal partition with glass doors opposite the section switches.

Short Circuits caused by Cats, Rats and Mice. With this arrangement, short circuits in the E.H.T. busbars were too frequent to be pleasant, and these short circuits were found to be due to cats, rats and mice. The cats, or at any rate some of them, were officially on the staff, their job being to keep down the rats and mice; but when it was found that a cat had caused a short circuit, with dire results to the cat, it was decided that all openings large enough to admit a cat, must be closed up. This was done, but unfortunately there were still openings through which the rats and mice could enter the E.H.T. chamber, and the cats were unable to get at them. It is astonishing what a large gap can be bridged over by a rat or a mouse, if one reckons in the tail—which by the by is quite enough of a conductor to pass sufficient current to start an arc. The short circuits, therefore, continued, and the next step was to coat the busbars with some insulating material. Unfortunately the resinous nature of the insulating tape or empire cloth had a great attraction for the rats and mice, and after gnawing for some time, they got on to the bare copper, and another short circuit occurred.

Short circuits between phases and to earth have also been caused in this type of busbar by the operation of the section switches, and by faulty handling of the metal hook mounted on a wooden pole, by which these switches are worked.

Stone Cubicles. The next step was to entirely enclose the busbars and section switches in stone cubicles with iron doors at the back and wired glass doors in front, and to put insulating partitions between the phases at

every point where access was possible from the front. The doors fitted closely, so that no rats or mice could get in. This was an enormous improvement, and this stone cubicle system is in use at the present day for the machine busbars and isolating switches.

Ironclad Type. The final development for the feeder busbars was to insulate the busbars thoroughly, enclose them in iron casing, and fill in between with compound, as is done in the Reyrolle type. There are undoubtedly very great advantages to be gained by using the armour-clad busbars and switchgear. These advantages may be briefly set out as follows:

Complete protection is given to the switchboard attendants from electric shocks, and from the burns which nearly always accompany these shocks. This protection is due to the fact that all high-tension conductors are completely enclosed, and it is impossible for the attendants to touch any live portions of the busbars or switches.

This enclosing of the live parts does away with the necessity of cleaning and inspection, both of which have been sources of danger in the case of busbars, which are mounted on insulators and surrounded only by air.

The busbars are covered with a varnished tape to a thickness of about half an inch, and the space between the busbars is entirely filled in with an insulating compound, which sets like pitch.

This arrangement has several advantages. It eliminates the air and the moisture it may contain, prevents the access of conducting vapours, and the solid nature of the compound prevents any danger of the busbars being attracted together when very heavy currents pass, due to a short circuit on some other part of the system.

Another advantage which this type of switchgear possesses, in common with the draw-out cubicle type, is that the switch is racked out entirely clear from the live terminals before access can be obtained to it, so that it is impossible to get a shock when examining or cleaning the switch.

The disadvantages of the ironclad type are that it is

expensive, and if anything goes wrong with the potential transformers, which sometimes have to be used in conjunction with the switches, it is very difficult to get at these transformers, as they are embedded in compound. Some of the latest designs of armour-clad switchgear provide means of access to the transformers, but it is generally agreed by manufacturers and users that potential transformers should be eliminated wherever possible.

Having now set out the advantages and disadvantages of the ironclad type, a description of one of the designs manufactured by Messrs. Reyrolle & Co. (the originators of this type) will be given.

Reyrolle Ironclad Switchgear. The complete switch panel consists of two main standards projecting forward, as shown in the illustration, the front horizontal portion being provided with racks, by means of which the oil switch is racked away from the fixed busbars, which are attached at the back of the standards.

The fixed portion consists of a set of three busbars mounted in triangular formation inside a cast metal chamber, supported from the main frame standards (see Fig. 22). Each busbar is connected to a socket supported by a large tubular insulator, fixed in a spoutlike aperture to the front of the busbar chamber. Immediately under the busbar chamber, another chamber is provided to accommodate the current transformers, and the size of this chamber depends upon the number of transformers that are required to work the various protective devices and instruments. If a potential transformer is required, this takes the form of the totally enclosed oil-immersed type, and is mounted in front of the chamber.

The E.H.T. fuses which protect the transformer are of the plug type, and are inserted into tubular insulators embedded in the hood of the transformer case and the main chamber. A cable dividing box provided with three apertures, to which glands can be fixed, is mounted on the lower side of the transformer chamber. If a three-phase cable is brought to the switch, two of the apertures are blocked and the centre one only is used; but if it is

desired to bring three single-phase cables to the switch, all three holes are provided with glands.

The movable portion of the switch panel consists of complete ironclad oil circuit-breaker mounted on standards provided with rack and pinion; this breaker can easily

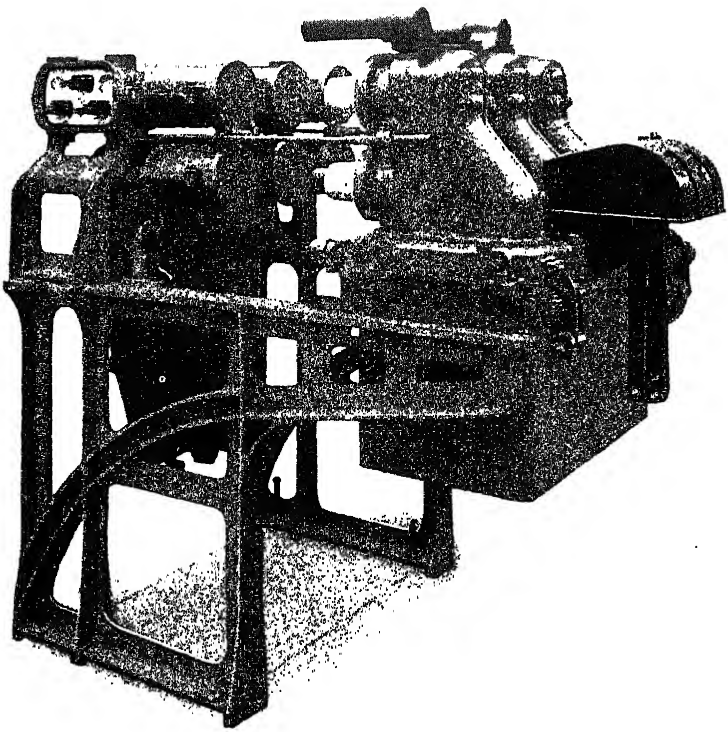


Fig. 22.—Reyrolle Ironclad Drawout Switchgear, Type B.

be moved forward clear of the busbars, thus completely isolating the switch, and enabling it to be examined with complete safety. The plug contacts shown in the illustration projecting from the front of the switch, engage with the sockets in the busbar and transformer chambers, and thus connect to the cable. As the circuit-breaker moves forward, it actuates folding doors which close over

the spout openings in the fixed chambers, and thus prevent anyone getting access to the live conductors.

A portable truck with a moving platform is used for lowering the heavy tanks when a circuit-breaker is withdrawn or for moving a switch bodily.

Truck Type Draw-out Ironclad Switchgear. This type of switchgear, which is very largely used in this country, has many advantages over the stone cubicle type with fixed switch, and is only second to the ironclad, compound filled type which has already been described.

The advantages over the stone cubicle type are :—

(1) Safety.
(2) Accessibility.
(3) Compactness.

(1) *Safety.* The whole of the working parts, *i.e.* circuit-breaker, current transformers, potential transformers, are mounted on the movable portion and can be entirely withdrawn from the busbars for cleaning and inspection.

A safety interlock prevents the truck from being wheeled in or out of its cubicle while the circuit-breaker is closed. In addition, a self-locking device—fitted on the bottom of the truck panel—so engages with the rails that the truck is held in position and must be released by the operator before the truck can be withdrawn. The isolating contact blade by means of which contact is made with the busbars during the withdrawal of the truck, is immediately covered with automatic shutters, so that accidental contact with live parts is impossible.

(2) *Accessibility.* When the truck is withdrawn everything on it is dead, and circuit-breakers, transformers, etc., can be repaired or cleaned with great ease.

(3) *Compactness.* Owing to the walls of the fixed cubicle being made of steel and the compactness of the arrangement, the gear occupies less space than the stone cubicle type.

Although the Truck Type switchgear is not quite so safe as the compound filled, as there are bare parts exposed, yet it possesses a distinct advantage in that the trans-

formers, both current and potential, are easily accessible for cleaning and repair or alteration.

Description. It consists, as shown in Fig. 23, of two units: (1) Fixed cubicle unit; (2) Movable truck unit. The framework for each unit is built up of steel sections with electrically welded joints.

Busbars and connections are of hard-drawn high-conductivity electrolytic copper, which is arranged and painted with colours in accordance with the requirements of the British Standard Specification.

Fixed Cubicle Unit. This is totally enclosed by sheet steel and is divided into three chambers, as shown in Fig. 23—truck chamber, cable-box chamber and busbar chamber. The framework for this unit includes the rails and guides for the movable truck, and these rails are inclined at the ends to facilitate entry of truck and to prevent shock. A switchboard can be assembled by bolting together a number of these units. The sheet steel sides are so arranged as to permit a continuous busbar chamber throughout the length of the switchboard; the ends are enclosed by removable sheet steel plates or cable boxes. Isolating contact blades with connection studs for carrying the busbars or incoming or outgoing cable terminals are fixed within substantial porcelain insulators firmly secured to framework by adjustable clamps. These blades are completely shielded from accidental touch by automatic shutters which close over them during the withdrawal of the truck.

Movable Truck Unit. The truck frame is of an open type construction permitting easy inspection and maximum accessibility to all parts when the truck is withdrawn. The truck carries the circuit-breaker instrument transformers and a set of isolating contact jaws which engage with the contact blades in the cubicle when the truck is in position, thus completing the circuit. These contact jaws are carried by substantial porcelain insulators firmly secured to the frame by adjustable clamps. Mounted on the front of the frame is a sheet steel panel upon which are assembled the circuit-breaker, operating handle and

trip coils, necessary instruments and indicating devices. A safety interlock prevents the truck from being wheeled in or out of its cubicle while the circuit-breaker is closed.

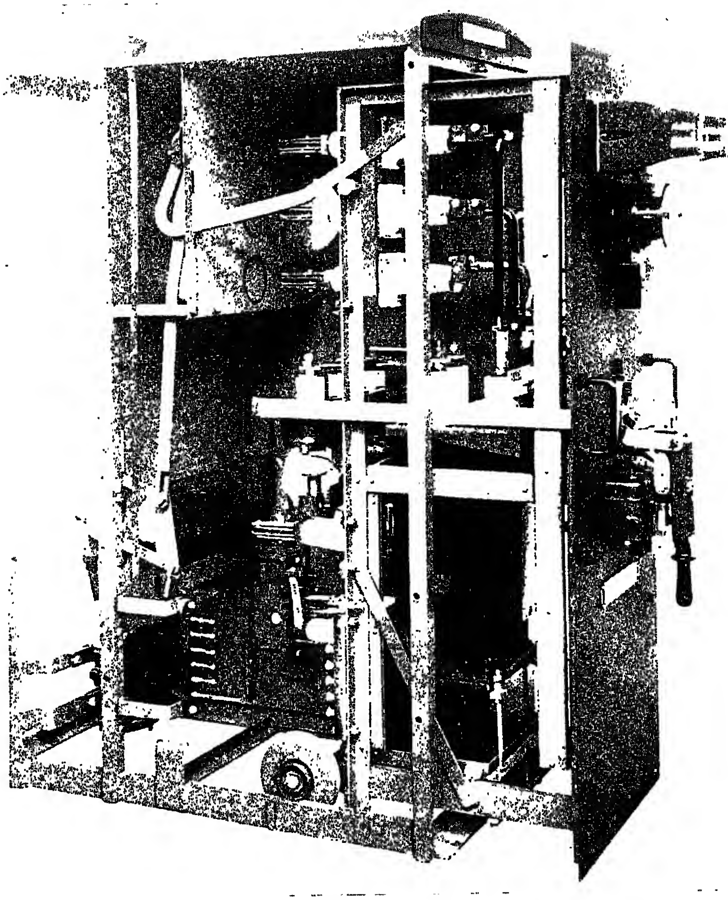


Fig. 23.—Truck Type Draw-Out Ironclad Switchgear.

In addition a self-locking device prevents the truck from shifting and must be released before the truck can be withdrawn. In some cases the truck is provided with three wheels, which make it easier to manœuvre when the truck

is withdrawn, and these wheels are fitted with roller bearings which greatly facilitate the movement of the truck. The space underneath the circuit-breaker provides accommodation for an oil-immersed potential transformer, and this transformer is mounted on a wheeled carriage so that it can be easily removed whenever it is necessary to lower the circuit-breaker oil tank for inspection or cleaning.

All parts are carefully assembled in jigs to ensure the interchangeability of all similar trucks of the same form and rating. This is a great convenience, as if a particular switchboard equipment requires overhauling continuity of service can be maintained by inserting a truck from another circuit which is not in use for the moment.

The Oil Circuit-Breaker. In E.H.T. circuits the oil circuit-breaker is universal and there is no other type of switch which will deal with large amounts of power in the space that is available. Ratings of 200,000 and 500,000 kVA. are quite common, and a considerable number of large switches have been constructed which will successfully interrupt a circuit in which 1,500,000 kVA. is flowing. Length of break, quantity of oil, effect of magnetic blow-out, strength of tank, all have to be taken into consideration in the designing of a successful switch.

Length of Break will not of itself ensure a successful rupture, and although some excellent results have been obtained with switches having a 12-inch break and a small quantity of oil, other switches having only a 2-inch break but a much larger volume of oil have given satisfactory results. There is a danger, however, in short breaks, as the arc may be maintained although the switch has opened to the full extent.

The Magnetic Blow-out is useful and shorter gaps may be used where it is employed, for the arc is blown out longer before the final extinction.

The Volume of Oil in the switch is of very great importance, and tests have shown that a tank which was capable of withstanding a steady internal pressure of

100 lb. per sq. inch burst in trying to clear a short circuit of 150,000 kVA., whereas another tank tested to only 50 lb. per sq. inch, but which had three times the volume of oil, satisfactorily ruptured a circuit of 200,000 kVA.

The Velocity of Break is another matter of vital importance, for it is clear that the higher the velocity of the contacts the greater the distance separating them when the zero point in the current wave is reached, and the less the chance of a re-establishment of the arc, at the next wave. This speed is obtained by a spring kick-off action, and the strength of the spring is only limited by the resistance it offers to the closing of the switch.

Head of Oil above Point of Break. At the instant of separation of the contacts a bubble of conducting vapour is formed, and although it would seem desirable to have a small head only so that the bubble can get away quickly, on the other hand there is a danger of a persistent arc being set up across the insulators between the conductors and the top plates of the switches. It is better, therefore, to have a good head of oil, although this brings in another disadvantage, viz. that the inertia of the oil above the break increases the strain on the sides and bottom of the tank.

Construction. A typical switch is shown in Fig. 24. It consists of a framework supporting six terminals which pass through porcelain insulators and terminate below in six sets of self-aligning contact fingers which in practice are immersed in oil in the tank. These contact fingers are renewable, and are reinforced by strong springs which help to maintain good contact.

The movable part consists of three wedge-shaped copper blades thoroughly insulated one from the other and mounted on three rods which are connected together on the top of switch and attached to suitable cranks and levers for operating. These copper bars are below the contact fingers, so that if anything happened to the switch, causing it to move, it would break and not make circuit. To switch on the three copper bars are forced upwards

into the contact fingers, which being self-aligning ensure good contact. The oil tank is of welded sheet steel, lined with insulating material and barriers of this material are placed between the phases. A detachable winch mechan-

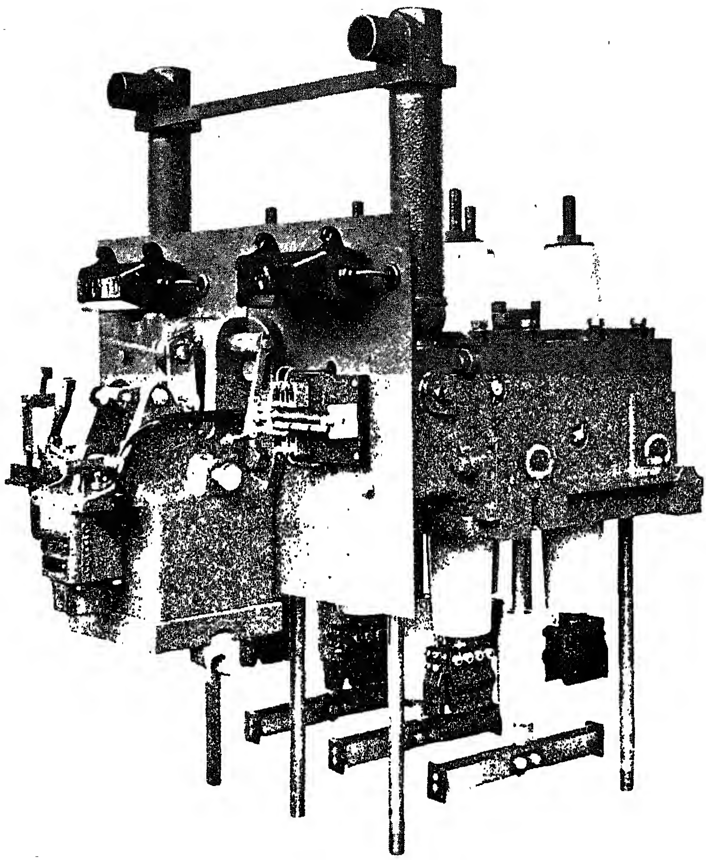


FIG. 24.—Typical E.H.T. Oil Switch.

ism for lowering or raising the oil tank is provided, one only being necessary for all the breakers of similar size installed in one station.

For **direct hand-control** the operating handle and

escutcheon are mounted on the front of the control panel, with the circuit-breaker directly behind.

For **remote hand-control** the operating handle and escutcheon is mounted on the control panel and connected by suitable bell crank levers and way shafts to the switch, which may be some distance away.

For **solenoid control** the solenoid mechanism is mounted on channels which are fixed directly to the breaker. This is worked by a switch placed in any suitable position, or in the case of automatic stations by a relay. Solenoid operated breakers are fitted with shunt trip only, their operation on overload under voltage, etc., being accomplished by suitable relays, but with the hand-operated breakers these automatic trip coils can be embodied in the switch itself.

Danger to Life from Shocks and Burns

Reference has been made in another part of the book to the shocks and burns which result from the touching of any live parts of busbars or switches, and a few remarks on the regulations which have to be drawn up to prevent this happening may be of interest. Opinions vary greatly as to the advisability of making regulations either short and concise, so as not to confuse the attendant; or, on the other hand, to endeavour to cover all possible eventualities, which necessitates a large number of lengthy regulations. It is impossible to make these regulations foolproof, and however carefully they are drawn up, it is almost certain that they cannot cover every case that may arise. The following set of regulations, from the author's experience, may be taken as covering most points that arise in a substation. The switches controlling the mains are of the Reyrolle type, and the isolating switches of the cubicle type.

Regulations.

1. In case of repair, testing, or cleaning any part of the E.H.T. converting plant or connections, the substation attendant must first open the isolating switches connect-

ing to the busbars, and the doors giving access to these switches must then be locked. A "Danger" label must be attached to the panel controlling the above plant.

2. When cleaning any part of the E.H.T. busbars or cubicles, the charge engineer must rack out the switch controlling the machine busbars, and lock the busbar section. He must then test with the Partridge detector to see whether the busbars are alive, and being satisfied that they are dead, must connect all three phases together and to earth.

3. In case of repair or testing of any of the E.H.T. busbars or cubicles, the charge engineer must entirely isolate the particular section upon which work is to be done, by means of the sectional switches provided, and the doors giving access to these switches must then be locked. Before any work is begun, the bars must be tested with the Partridge detector to make sure that they are dead, and then earthed and short-circuited. They must remain in this condition except during the actual period of test.

4. When any machine is in motion, whether driven from the E.H.T. or the L.T. side, all connections must be considered as under pressure, and the necessary precautions taken to prevent accidents.

5. In short-circuiting any part of the E.H.T. system, only the apparatus provided for the purpose must be used, and this must be properly earthed first.

6. Any isolating switches or fuses forming part of the E.H.T. system must only be removed and replaced by insulating tongs or rods provided for the purpose.

7. In case of cessation of supply from the generating station for any reason, the whole of the E.H.T. system in the substations must be regarded as being under pressure, and all necessary precautions followed.

8. Under no conditions may any person enter any of the E.H.T. enclosures, or carry out work on any connections whilst they are under pressure.

9. In the event of any feeder or interconnector switch opening in any of the substations, the substation attendant

must at once ascertain from the generating station or other substation, as the case may be, to which the feeder or interconnector goes, whether the corresponding switch has also opened. If the switches at both ends of the main are found to be out, they must be racked out and padlocked, and the matter reported to the mains engineer as soon as possible. If, however, the substation attendant finds that the corresponding switch at the other end of the cable has not opened, and the main is still under pressure, he can reclose the switch, simply logging the circumstances.

10. When a main has been ascertained to be broken down, the charge engineer of the substation, or generating station as the case may be, will take possession of the keys of both the busbar and feeder sections, and will hand the key of the busbar section to the mains engineer in charge of the repairs, keeping the key of the feeder section in his own charge. The mains engineer must not start on the work of breaking down on any cable in the street, until he is in possession of both keys of the busbar sections.

11. When a feeder or interconnector has been under repair and the repairs are finished, the mains engineer will hand back the keys to the charge engineers at each end. The charge engineer, on receiving the key, will ascertain by communicating on the telephone with the charge engineer at the other end, that he has received his key. After having checked the phases and ascertained that everything is clear, the substation charge engineer will rack his switch in and close it. After this has been done, the charge engineer at the generating station will rack in his switch and close it.

12. In no case must any duplicate keys be kept. In the event of a key being lost, the padlock is to be scrapped and replaced with an entirely new lock and key.

The Partridge Detector. The Partridge detector mentioned in the above regulations is a very simple but useful piece of apparatus for determining with perfect safety to the operator, whether any bare conductors are alive. It is illustrated in Fig. 25.

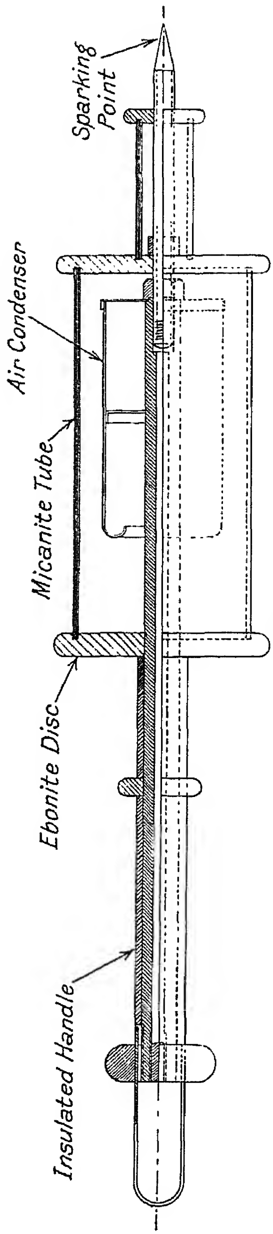


FIG. 25.—Partridge Pressure Detector.

The apparatus consists of an air condenser fitted to a long insulated handle and provided with a discharging point. The body is made of a micanite tube, and inside there is a tubular lining made of thin copper sheeting. An insulating rod runs through the centre of the cylinder, and into it is screwed a $\frac{3}{8}$-inch steel rod, this projecting for a short distance inside the cylinder of copper sheeting. To the end of the rod is fixed a steel point, which is protected by a removable fibre cap when not in use. The detector is held by the end of the insulated handle and presented to a bare part of the contact or bar to be tested. If this is alive, a stream of sparks passes to the steel point.

The Human Element. In spite of all regulations, occasions will arise where the attendant, due to carelessness or temporary aberration, will touch some live conductor and get a severe shock. A very usual pressure in a substation is 11,000 volts, and if the neutral point is earthed, a man standing on the floor or platform connected to earth would get a shock of about 6,400 volts if he touched one terminal of the three-phase system. A man doing this would, according to general expecta-

tions, be killed instantly, but this is not necessarily the case. The two following cases, which are within the experience of the author, show how difficult it is to be dogmatic as to the pressure necessary to destroy life.

Case 1.—Some work had been done on a section of the E.H.T. busbars, and this section had been made dead by means of isolating switches mounted in stone cubicles. The attendant was informed that the work had been finished, and was asked to make this section alive again. Instead of using the insulated rod with brass hook on the end, which was provided for closing the isolating switches, he put his hand into the cubicle and attempted to close the switch, with the result that he got a shock of about 6,000 volts. The shock knocked him down, and as he drew his hand away, an arc was started which went to earth and brought out the switch at the generating station. The man jumped up almost immediately and cursed himself for being a fool. His arm was, of course, badly burnt, but after he had been to the hospital and had it bandaged, he wanted to go on with his work, which, of course, he was not allowed to do. He apparently suffered no injury from the shock quâ shock, and after his arm had healed up, which took some weeks, resumed his duties as usual. An examination of the sole of his boot showed a small hole burnt round the edge where the current had passed to earth.

Case 2.—A man on night shift, whose duty it was to clean the insulators supporting the E.H.T. busbars, disregarded all the regulations and precautions which had been provided for his safety, and started to clean the insulators with the busbars alive. After cleaning for some time, his hand came into contact with one busbar and his elbow in contact with another, his other hand being on the ironwork which was connected to earth. He therefore got a shock of 10,500 volts from hand to elbow, and 6,000 volts right through his body to the other hand. The hand and elbow were badly burnt, and there was also a bad burn on the hand which rested on the iron. This man was treated at the hospital, and the next day

came in to report as to how the accident happened, being apparently none the worse for his experience except for the burns.

It has been suggested that a shock need not be fatal unless the current passes through some vital part of the body, but in the first instance above, the current passed from one hand right through the body and out at the foot, and in the second, from one hand right through the body to the other hand. The ages of the men involved were fifty-five years and twenty-four years respectively.

From the above, it is clear that no definite statement can be made as to the voltage of a shock which will have fatal results. It is well known that persons have been killed by shocks of 200, or even 100 volts, and in most of these cases it will be found that the area of contact with the body was large, as is the case when a person is in a bath and touches a live terminal, or the person receiving the shock was in a very feeble state of health. It is now generally agreed that fatal results depend more upon the constitution and health of the individual than upon the voltage.

The obvious remedy is to so enclose all live parts that an accidental shock is impossible.

CHAPTER V

PROTECTIVE DEVICES FOR E.H.T. CIRCUITS

It has been pointed out that the word "protective" is wrong in this connection, as the devices and systems dealt with in this chapter do not prevent the fault from occurring, but only come into operation after the fault has shown itself. This is quite true, but it must be borne in mind that the object of the devices is to cut out the faulty cable or machine without disturbing the rest of the plant, and therefore they may with truth be said to protect the system as a whole.

When an engineer who has a large electrical scheme to design sets out to decide the particular kind of protective gear he will instal, he is confronted with a large number of different systems, each claiming to possess some special advantage; and as it is impossible for him to have had experience with all these systems, he generally endeavours to obtain from his brother engineers the results of their experience with the particular systems that they have put in.

Here he meets with considerable difficulty, as the experience of one often seems to contradict that of another, and he probably sighs for the old days of simplicity, when an overload fuse or circuit-breaker was the only protective device possible. After examining the matter a little further, he reluctantly comes to the conclusion that with present-day loads, sizes of machines and cables, the old system is impossible, and in order to prevent severe damage to his plant he must instal one or more of the up-to-date systems.

Fuses. The author about twenty-seven years ago

started with an 11,000-V. three-phase system, in which no circuit-breakers of any kind were installed. The whole of the protection was by means of fuses, and at the beginning air fuses were used. These proved unsatisfactory, and were shortly replaced with oil fuses.

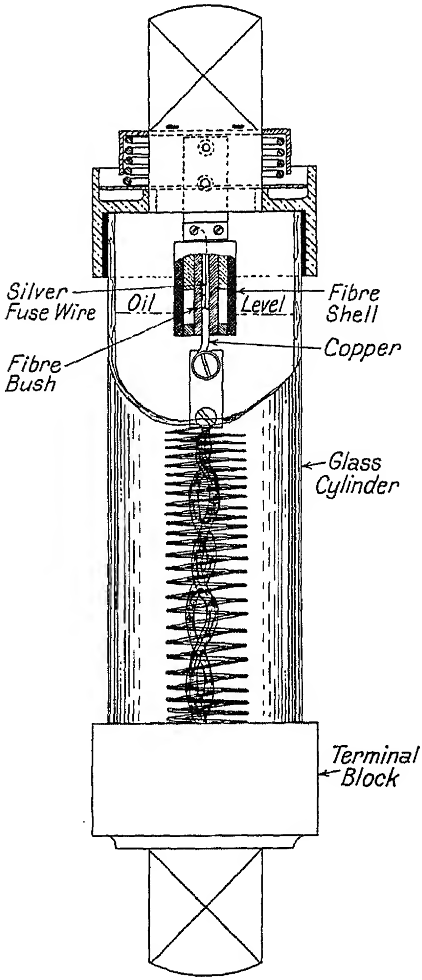


FIG. 26.—Silver Wire Fuse Breaking under Oil.

There is a good deal to be said for an oil fuse if used for moderate powers, and especially for that type which uses a silver wire immersed in oil, with a spring attached to it so that when the fuse goes, the arc is drawn down under the oil. The fuse has an inherent time lag, and this varies inversely as the current, as obviously the time taken to fuse the wire will be much less with a large current than with a small one. Fig. 26 illustrates one of these oil fuses, and the author has seen a 4,000-kW. generating set switched direct on to this without breaking the glass cylinder, the circuit being opened satisfactorily.

However, it had to be acknowledged that with the huge powers now employed, something better than the oil fuse

was necessary, as the danger to life by explosion and the cost of the repairs to machines was too serious to face with equanimity.

Circuit-Breakers. Oil circuit-breakers were next employed with overload coils, but the great difficulty here was to prevent the healthy machines and feeders being tripped by the very large currents which passed through them on the way to the faulty cable or machine.

Some sort of discrimination, therefore, had to be introduced, and this took the form of a time lag, which with circuit-breakers set for the same overload current enabled one to decide which should come out first. This still did not prevent more machines and feeders coming out than was necessary in order to clear the fault, and the attention of designers was therefore turned to devising a system which should cut out the faulty feeder or machine and leave the other undisturbed.

Merz-Price Balanced Protection. The introduction of the Merz-Price balanced protective gear was a great step in advance, and it is with this gear, or modifications of it, that the great majority of systems now being installed are protected.

The underlying principle on which the Merz-Price system is based is that, if a cable is without fault, the current that enters at one end must be the same as that which leaves it at the other end. If now we place a transformer (the primary of which is the cable itself) at each end of the cable, and connect the two secondaries through pilot wires which pass through relays, no current should pass through these pilot wires, as the transformers will be balanced. This is illustrated in Fig. 27, which for the sake of simplicity is shown for one phase only, the opposing arrows indicating that no current is flowing.

If now a fault to earth occurs on this cable, the current that enters at one end will no longer be the same as the current which leaves at the other end, the transformers will not be balanced, and a current will flow along the pilot and through the relays, which in closing will trip the switches at the two ends of the cable. The condition

of affairs is shown in Fig. 28, and it should be noticed that even supposing the fault was to occur exactly in the middle point of the cable, and the current supplied from each end was exactly the same, the current in the one transformer will now be reversed with respect to the other,

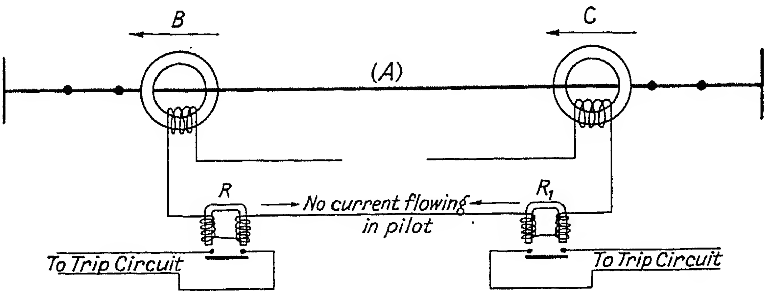


FIG. 27.—Merz-Price Balanced Protection System. No Fault, Trip Circuit Open.

and the potential on the secondary side of the two transformers, instead of balancing one another, will now be added one to the other, and will cause a current to flow through the relays.[1]

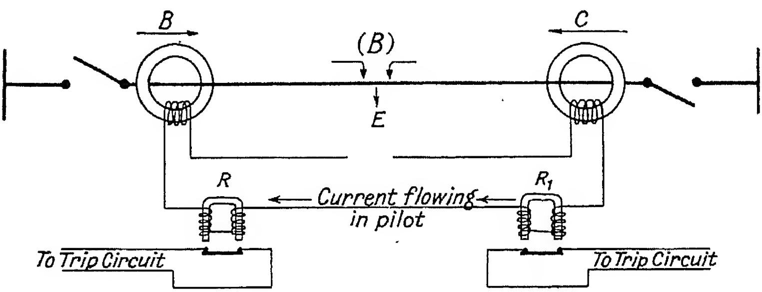


FIG. 28.—Merz-Price Balanced Protection System. Earth on Cable, Trip Circuit Closed.

Fig. 29 shows how the system will cut out a faulty cable without disturbing another cable, which is in series with it. It is assumed, of course, that the cables are fed from both ends, *i.e.* they form part of a ring main. In

[1] Owing to the fact that the primary of the transformers is a single conductor, it is necessary, in order to get sufficient ampere turns, that the fault current shall not be less than about 400 amperes.

this case, the fault causes the two transformers at each end of B to be out of balance, and these, by means of the relay, trip the switches at each end of B. The current through the two transformers on A is the same and the secondaries remain in balance, leaving the switches at each end of A closed, and as the cable is fed from the left, it remains in commission.

The system as described above would appear to be nearly perfect; but unfortunately in actual practice several difficulties arise, which, if not surmounted, cause the gear to trip out healthy feeders and machines. We assumed that the transformer at one end of the core of a cable was identical with the transformer at the other end of this core, and that no matter how great the current in the core, as long as the same current passed through the two transformers, they would remain in balance as far as the secondaries were concerned, and therefore there would be no current passing through the relays. These transformers are very carefully balanced one with the other, at as high a current as is practicable; but when there is a short on another part of the system, the current (usually called the straight-through current) in the cable may rise to as much as 20,000 amps.

It will be readily understood that if, owing to some slight difference in the iron or the air gaps in the two

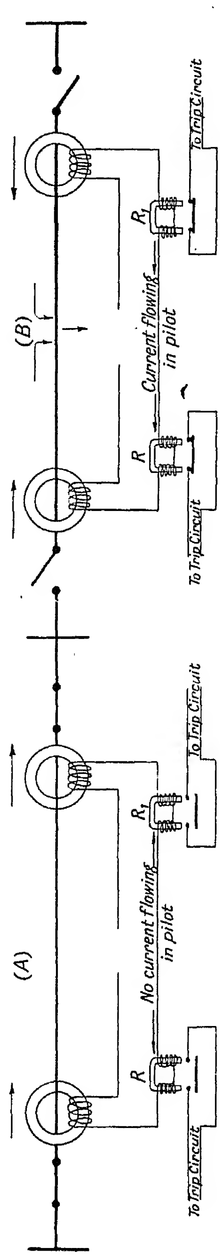


FIG. 29.—Merz-Price Balanced Protection System, showing how a Faulty Cable can be cut out without disturbing another Healthy Cable which is in series with it.

transformers, one of them reaches saturation point before the other, an out of balance will be established, and current will pass through the relays, causing the cable to trip, although there is nothing wrong with it. At first, each transformer was balanced with another forming a pair, and these two were always kept together. This led to difficulties, and later each transformer was balanced against a standard, thus avoiding the necessity for pairing.

Another device to render the voltage characteristics of the transformers similar was to introduce air gaps in several parts of the iron circuit, thus preventing saturation of the core until extremely high currents are reached. This has the disadvantage that it renders the apparatus less sensitive, and increases the current that must flow when a fault occurs, in order that the relay may trip the cable. Another difficulty is due to the capacity of the pilot wires themselves, which is quite considerable, especially in long cables. When a straight-through current of 20,000 amps. passes through a healthy cable, the potential generated in the secondary of the current transformer reaches quite a high figure, and the charging current in the pilot due to this pressure, is in some cases quite sufficient to cause the relay to act and bring out the cable.

Beard Sheathed Pilot System. The cure for this trouble is to use the Beard Sheathed Pilot System. In this system, the secondary wire connections of which are shown in Fig. 30, each pilot wire is provided with a copper sheath, which is insulated from the pilot wire and from earth. This sheath is not continuous, but is cut at the mid-point of the cable that is to be protected.

Fig. 31 shows the secondary connections of the ordinary Merz-Price protection, and it will be seen that the capacity current in the pilots has to pass through the relays. In Fig. 30, however, the transformers are starred through the relays, and the capacity current which goes out through the pilot, returns through the sheath without passing through the relays. This does away entirely with this pilot capacity trouble, but the pilots are more costly, and the thin copper sheathing is not good from a mechanical

point of view and is difficult to joint. Further, this system necessitates a special operation in cutting the sheath at the mid-point.

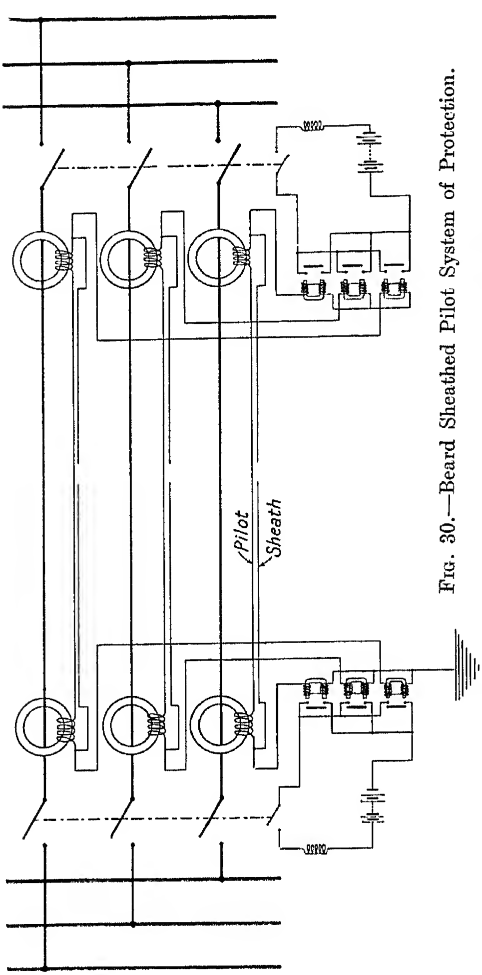


FIG. 30.—Beard Sheathed Pilot System of Protection.

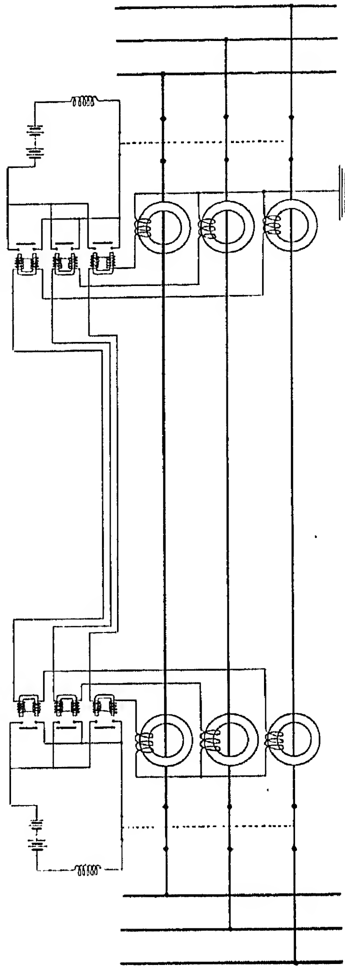


FIG. 31.—Merz-Price Balanced Protection System, showing the Three Phases.

Another scheme which the author has had in use for some years is described below.

The Diverter Relay System. This system employs only two pilots, and these are unscreened. It therefore

introduces a considerable saving in capital cost as compared with the ordinary system with three pilots fitted with compensating sheaths. The saving is said to be as much as 60 per cent. The two pilots, however, do not give complete protection, and an earth leakage feature is necessary in addition.

Fig. 32 shows the diagram of connections, and it will be seen that there are two distributed air-gap current transformers, one on each of two of the phases (these deal with faults between phases), and a solid core leakage current transformer surrounding all three phases (this deals with faults to earth). The secondaries of all three transformers are connected in series, and through the two pilot wires to the similar group of secondaries at the other end of the cable. The operation under conditions of fault current to earth, can be 100 amps. or lower, and the fault setting between phases with this arrangement can be 200 amps. or lower.

The diverter relay, which has very little inertia and acts very quickly, is connected across the three secondaries which are in series, and consequently it always has a current passing through it proportional to the line current. It is, however, insensitive to the ordinary fault currents, and only comes into operation if a heavy straight-through current passes. Under normal conditions, the armature of the diverter relay is open, cutting out the shunt resistance, and leaving the Fawssett-Parry operating relay with its full degree of sensitivity; but when the heavy straight-through current passes, the diverter relay attracts its armature, and thus puts the desensitizing resistance in shunt with the Fawssett-Parry relay, rendering it inoperative.

The whole success of this scheme is dependent upon the diverter relay acting before the Fawssett Parry relay, and this is secured by making the moving parts very light, thus causing it to move very quickly, approximately 1/100 second. The Fawssett Parry relay, on the other hand, although it is set to act with a comparatively small fault current, is much slower in action, approximately 1/10 second.

All the above systems involve the use of pilots sheathed or unsheathed, but another system which gives the same protection, and which is certainly more satisfactory from a mechanical point of view, uses no pilots of any kind.

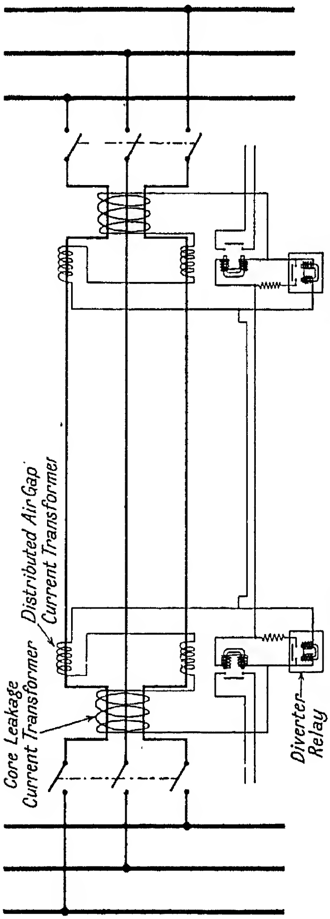


Fig. 32.—The Diverter Relay System of Protection.

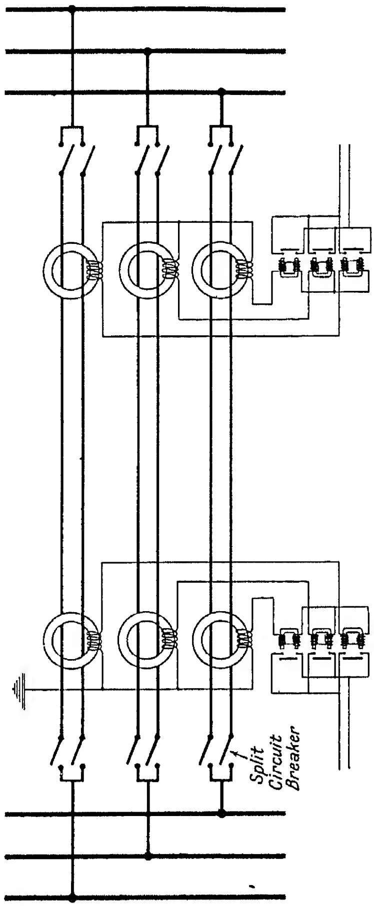


Fig. 33.—Hunter Split Conductor System of Protection.

Hunter Split Conductor System. This system, which is called the split conductor system, is due to Mr. P. V. Hunter, and it involves the use of a special six-core main cable, instead of the usual three-core. It therefore has no

advantage over the other systems from the point of view of expense.

The six conductors are arranged in three pairs, and the system depends for its operation on the principle that two conductors of equal resistance, when connected in parallel at their ends, carry equal currents, provided that the insulation is sound throughout their length. A fault on the insulation of one of the conductors permitting a current to flow to earth or to another phase destroys the equality, and use is made of this to operate relays at both ends which trip the circuit-breakers controlling this cable. The two conductors forming a pair, pass through a current transformer core in opposite directions, as shown in Fig. 33; and as long as the current in these two conductors is the same, no potential is generated in the secondary. As soon, however, as one core goes to earth or to another phase, this balance is destroyed and the relay acts. A defect of this system is that if a fault occurs at one end of a feeder which forms part of a ring main, the circuit-breaker at the end near the fault trips immediately, but the one at the far end remains closed, the impedance of the two parallel paths from the far end to the fault being nearly equal. To obviate this, split circuit-breakers are used at each end, but these add to the expense, and introduce difficulties from an operating point of view.

This system is sensitive, as currents through the fault of about 40 amps. will be sufficient to cause the relays to act. It also, if the switch contacts are well fitted, is free from trouble with straight-through currents.

Machine and Transformer Protection

Howard Leakage Protection. By far the simplest device is the "Leakage Current to Frame Protection" (Howard); see Fig. 34. The transformer tank or the machine frame, must be placed on concrete or similar material, which must be reasonably dry, so that they are really insulated from earth, for very little current will pass through dry concrete. The tank or machine frame is connected solidly to earth by a conductor of considerable

size. A current transformer is slipped over the conductor, and the secondary of this current transformer is connected to a relay, which trips the switch controlling the machine or transformer.

It is clear that, when a fault occurs, all the current that flows to earth will have to pass through the current transformer primary, and the relay will cut out the faulty plant at once.

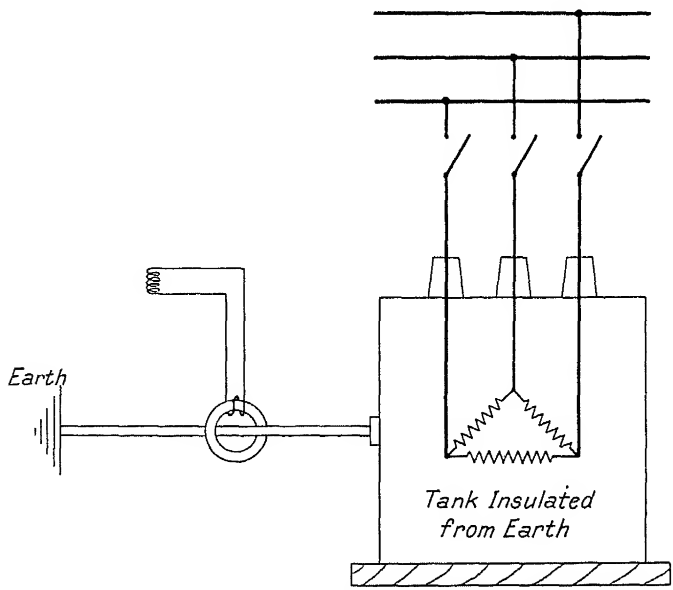


FIG. 34.—Howard Leakage Protection for Machines or Transformers.

Beard Self-Balance Protection. Another simple device is the "Beard Self-Balance System," which is an adaptation of the split-conductor system.

The principle of operation is that at any instant the current value throughout the length of each phase winding of the machine or transformer to be protected, is constant, or, in other words, is equal at each end of the winding. If then we pass each end of the winding through an iron core, the resultant flux in that core is zero, for the current in the two ends of the winding is equal but opposite in direction. By evenly distributing a secondary winding

on the iron core, an E.M.F. will be generated in this winding immediately any unbalance in the primary current exists. Such an unbalance is caused by a fault, such as a leak to earth from the main phase winding. This

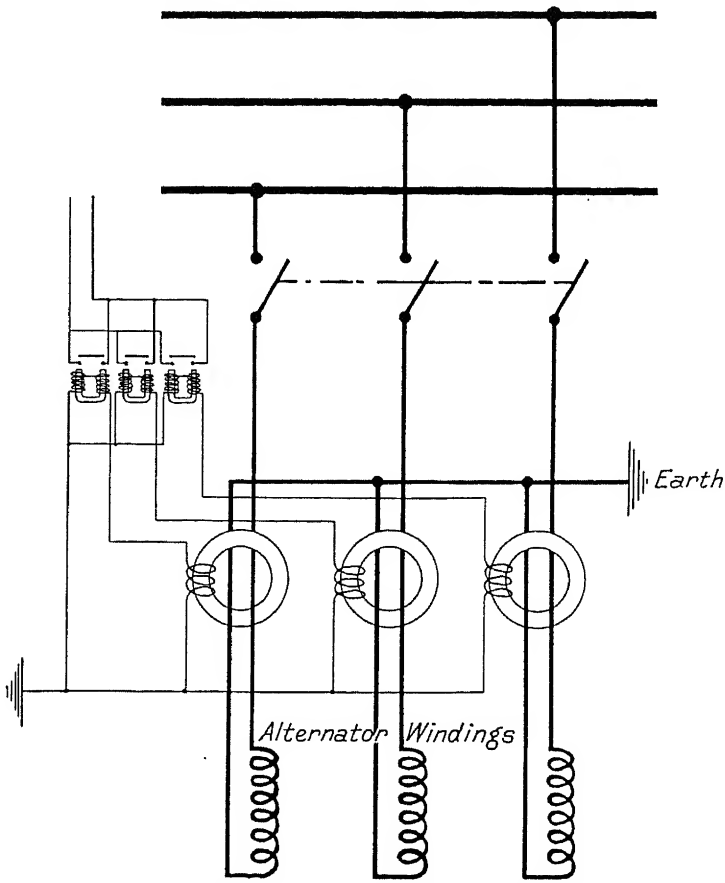


FIG. 35.—Beard Self-Balance Protection for Machines.

secondary E.M.F. is utilized in conjunction with a relay to trip the main circuit-breaker.

This system is less likely to give trouble due to heavy straight-through currents, as the primary currents are directly balanced against each other, and it is not a

case of balancing one transformer against another. In the case of transformer protection, each winding is separately protected, so that there is no need for adjustments to compensate for the unbalancing effect of magnetizing current, or from variation in ratio by tappings, and so a correspondingly low fault setting may be used, and still maintain a large margin for safety against inadvertent tripping on straight-through fault currents.

Fig. 35 shows the connections for this system.

CHAPTER VI

TYPES OF CONVERTING PLANT

Rotary Converter

A rotary converter may be described as a D.C. generator, with the addition that the armature winding is connected to slip rings as well as to the commutator. Rotary converters may be single-phase, two-phase, three-phase, or six-phase. The current in the armature winding of a rotary converter is the difference between the A.C. and D.C. currents, and this difference decreases by increasing the number of phases up to six.

Heating Factor. Fig. 36 gives some interesting curves, showing the heating factor of single-phase, two-phase, three-phase and six-phase rotaries, and how this factor varies with the power factor. The "heating factor" is the ratio of the C^2R losses when the machine is operated as a rotary, to the C^2R losses when the machine is operated as a D.C. generator.

It will be noticed that in the case of the single-phase rotary, this heating factor is very much larger than in the case of the D.C. generator, and with the three-phase, two-phase, and six-phase it is very much less. It is somewhat confusing at first to see that the two-phase rotary is better than the three-phase; but if one remembers that in the two-phase we have four connections to the armature and four slip rings, whereas in the three-phase we have only three, this difficulty disappears. Single-phase rotaries, as is obvious from Fig. 36, tend to get very hot, and as a matter of fact they are not a practical

proposition. Two-phase rotaries are quite good, but two-phase supplies are practically never used now.

On three-phase circuits, which are almost universal nowadays, we can use three-phase or six-phase rotaries; but, as there are obvious advantages from a heating point

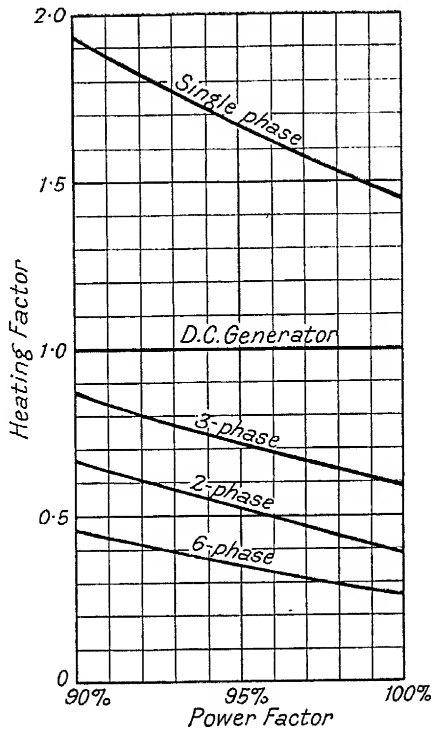


Fig. 36.—Curve illustrating the Heating Factor of Single, Two-phase, Three-phase and Six-phase Rotary Converters, as compared with a D.C. Generator.

of view with the six-phase, modern rotaries are usually made with six slip rings.

Overload Capacity. The overload capacity of a rotary converter is greater than that of any other type of converting apparatus. This is due to the low armature C^2R losses, good commutating and ventilating properties, and the cancellation of armature reaction due to the A.C.

currents and the D.C. currents. It also has a higher efficiency than any other type of rotating converter.

Fig. 37 shows the connections between transformer, slip rings, and armature of a rotary converter, and for simplicity the machine is shown as two-pole only. The E.H.T. side of the transformer is shown connected star, but it can equally well be connected delta. The L.T. secondary coils, of which there are three, are connected to six slip rings, and these rings are connected to six equidistant points around the armature, thus forming a six-phase supply.

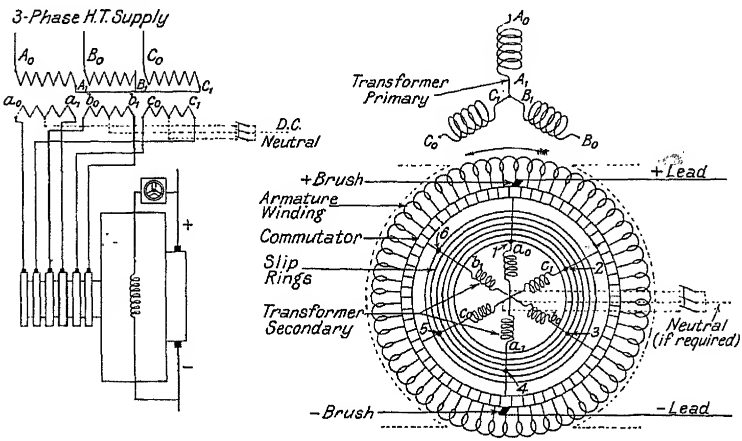


Fig. 37.—Diagram of Connections for a six-phase Rotary Converter.

Three-Wire System Connections. It will be noticed that a connection is made to the middle point of each of the secondary windings, and that leads from these points are assembled together to form the mid-wire, or neutral point of the D.C. supply. A little thought will show how this is possible. The potential across the secondary winding is continually increasing, decreasing and reversing, but the centre point of the winding always remains at a potential half-way between positive and negative. It is clear, therefore, that these points may be connected together, and so form the middle wire of the three-wire

D.C. system. If a load is connected between the neutral and the positive, the out-of-balance current will flow along the neutral wire and divide in the transformer, half passing through one side of the transformer and half through the other, the current finally passing through the armature windings to the positive brush. With 25 per cent. of full-load current out of balance, the difference between the two sides of the system can be kept below 0·5 of 1 per cent.

Regulation of Voltage.

There are four principal methods of obtaining this regulation: (1) Reactance control, (2) Booster control, (3) Induction regulator control, (4) Split pole control.

(1) **Reactance Control.** With constant A.C. voltage on the slip rings, the D.C. voltage remains practically constant, so that in order to vary the D.C. voltage, the A.C. voltage on the slip rings must be varied also. This can be done in spite of the fact that the voltage on the E.H.T. side of the transformer is constant by introducing reactance in the transformer, or by means of a separate external reactance.

If the field of the rotary is adjusted to draw a lagging current, the effect of the reactance is to lower the slip-ring voltage; whereas, if the rotary is adjusted to draw a leading current, the effect of the reactance is to raise the slip-ring voltage. It is obvious from the fact that in some cases lagging and others, leading currents are drawn from the transformers, that the power factor of the machine must vary from unity, but this variation is not great within the range of voltage required in practice. With 10 per cent. variation of D.C. and A.C. voltage, the power factor need not be less than 95 per cent.

The reactance method of control is by far the simplest and cheapest, and is all that is necessary on ordinary supplies.

Fig. 38 shows a 1,500 kW. Rotary Converter arranged for reactance control.

(2) **Booster Control.** This is accomplished by inserting

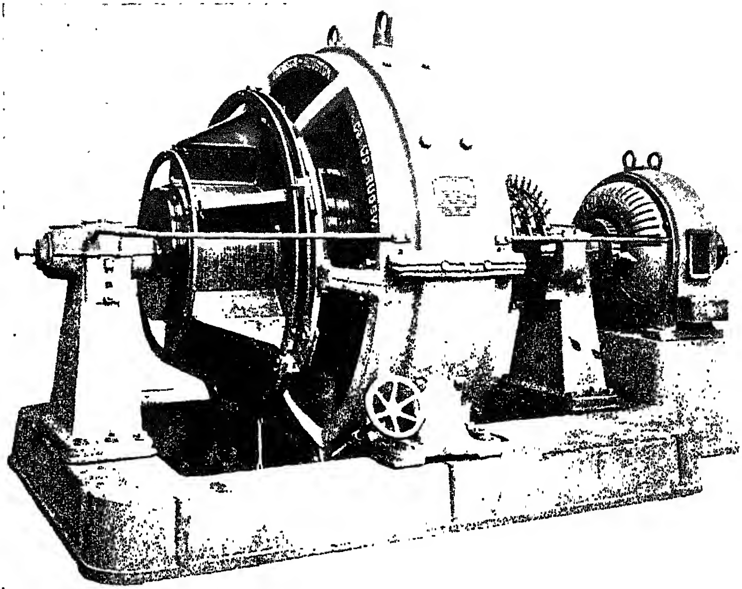


Fig. 38.—1,500 kW. Rotary Converter, arranged for Reactance Control.

an A.C. booster between the slip rings and the armature of the rotary. The A.C. booster increases or decreases

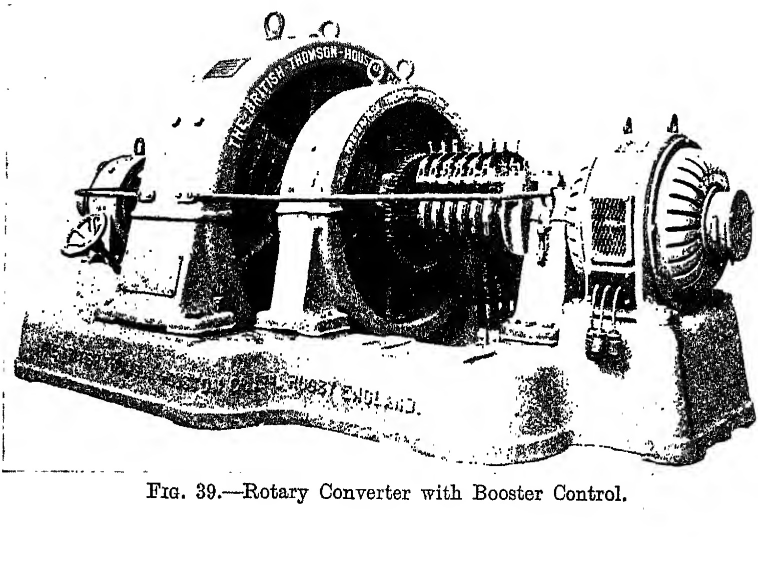


Fig. 39.—Rotary Converter with Booster Control.

the A.C. voltage applied to the rotary, and so raises or lowers the D.C. voltage. An illustration of a Booster Controlled Rotary is shown in Fig. 39.

If the rotary has no commutating poles, the booster arrangement works quite well, and the commutation is not affected. If, however, the rotary has commutating poles (this is usual nowadays), the commutation may be seriously affected, if the variation in voltage required is

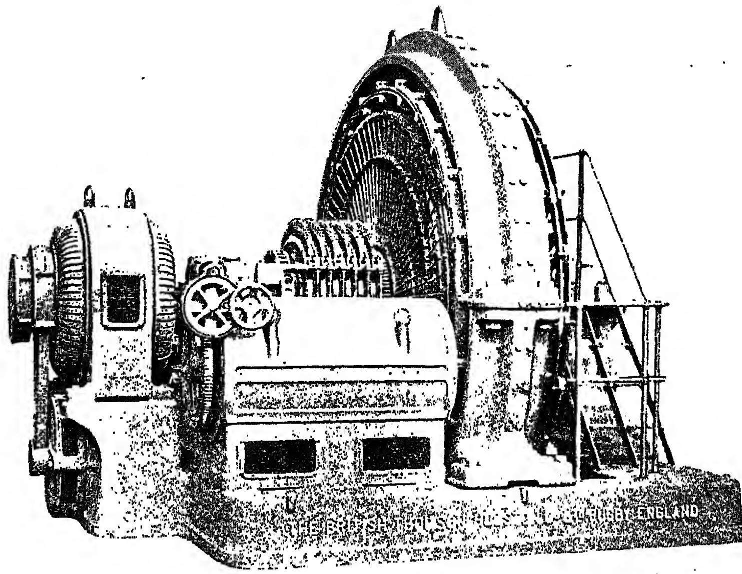


FIG. 40.—3,000 kW. Rotary Converter, with electrically operated Induction Regulator.

large. By the use of diverters and other schemes, the commutating may be improved, but this all means complication and is to be avoided.

(3) **Induction Regulator Control.** In this case, the induction regulator described on page 20 is inserted between the transformer and the slip rings. It increases or decreases the A.C. voltage applied to the rotary armature, and so raises or lowers the D.C. volts. The power factor is independent of load and voltage. Fig. 40 illus-

trates a 3,000 kW. Rotary Converter with electrically operated Induction Regulator.

(4) **Split-Pole Control.** This method, which up to the present has only been developed for twenty-five cycles, is suitable for a 25 per cent. range of voltage on either the A.C. or D.C. side. The main poles of the rotary are divided into two portions, the regulating pole and the main pole proper, as shown in Fig. 41. The main poles

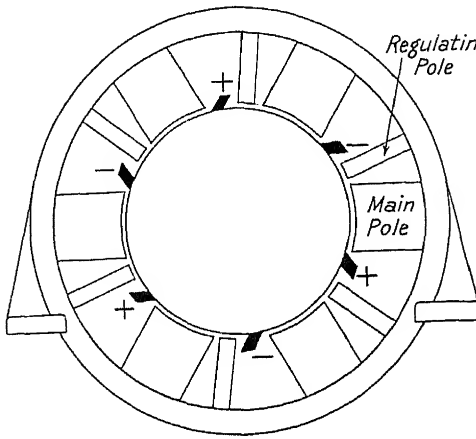


FIG. 41.—Field Structure for Split-Pole Rotary Converter.

are connected in the usual way, but the regulating poles are arranged so that they can be excited so as to oppose or assist the main poles. With constant voltage at the slip rings, the maximum D.C. voltage is obtained when the regulating pole is excited in the same direction as the adjacent main pole, and the lowest D.C. voltage is generated when the regulating pole is excited in the reverse direction to that of the adjacent main pole.

With this method of varying the D.C. voltage, unity power factor can be obtained under any condition of load and voltage. It is most suitable for small capacity 25-cycle machines.

Starting of Rotary Converters.

The two chief methods of starting rotary converters from the A.C. side are: (1) by taps on the transformer; (2) by induction motor on shaft. Rotaries can also be started from the D.C. side and synchronized just in the same way as alternators are put into commission, but this method is not often employed at the present time, although it possesses the advantage that the starting current is small.

Tap Starting. This is probably the simplest method of starting, and is used very largely in America for 25-cycle railway work. The slip rings are connected by means of a switch to one-half or one-third tappings on the transformer. The rotary runs up and into synchronism, the field circuit is then closed, and the machine thrown over quickly to full voltage tap.

The method has the advantage of being quick starting and self-synchronizing, but takes excessive currents which amount to from 50 to 100 per cent. of full load. Also with large machines provided with commutating poles (a very usual practice), sparking at the commutator becomes troublesome, and D.C. brush-raising devices have to be fitted, which is an undesirable complication.

Induction Motor Starting. In this case the induction motor, the rotor of which is attached to the shaft of the rotary, starts the converter and brings it up to synchronous speed. The stator windings of the induction motor, are in series with the converter armature at starting, and when up to synchronous speed, these windings act as a synchronizing reactance, and the converter automatically synchronizes with the supply. As soon as the converter has synchronized, the induction motor stator windings are short-circuited, and the converter is ready for supply. Fig. 38 illustrates a rotary converter with induction motor for starting.

This method has some advantage over tap starting, as there is no sparking at the commutator. Also the machine can be started up in about one minute, and only takes

about 35 per cent. of full load current from the E.H.T. mains.

Motor Generator.

This, as the name implies, consists of a motor and a generator coupled together, the motor being of a size to deal with the output of the generator, plus the losses. There are two types.

Induction Motor Generator. This consists of an induction motor coupled to a generator, and working

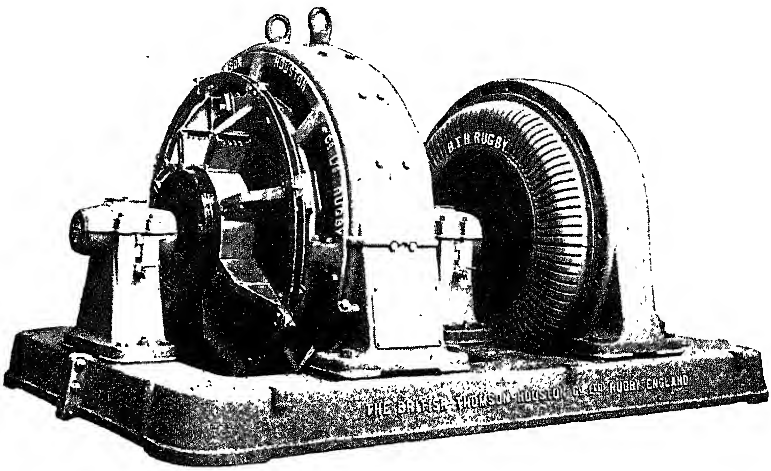


Fig. 42.—Typical Induction Motor Generator.

direct on the three-phase E.H.T. supply, which may be 6,000, 11,000 or even 22,000 volts. The latter voltage has not been used to any extent, but there is no inherent difficulty in winding stators for this pressure, and some makers are prepared to supply such machines. The motor is supplied with slip rings connected to a three-phase resistance, which is gradually cut out, and the D.C. machine can then be paralleled on to the busbars. Fig. 42 illustrates a typical Induction Motor Generator.

Synchronous Motor Generator. In this case, the machine consists of what is practically an alternating

current generator coupled to a D.C. generator (see Fig. 43). The D.C. machine has to be run up as a motor, and the A.C. end synchronized with the E.H.T. supply, the necessary variation of speed being obtained by varying the field of the D.C. machine. When synchronized, the position of the two machines is reversed by increasing the field of the D.C. machine, which then acts as a generator, and the A.C. machine as a motor, the speed, of course, remaining constant. The synchronous motor generator

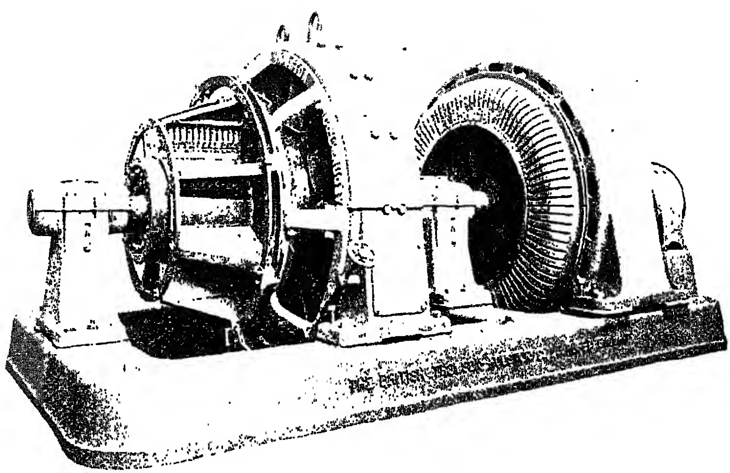


FIG. 43.—Typical Synchronous Motor Generator.

has a somewhat higher efficiency than the induction type, but suffers from the disadvantage that you must have other plant running on the D.C. side in order to start it.

Motor generators, owing to the fact that they have a much lower efficiency than other types of converting plant, are not very much used, but there are certain cases where they are preferable to rotary converters.

Motor Generator for Traction. A case in point is where it is desired to supply 3,000 volts D.C. for traction purposes. At the present time, makers are rather shy of manufacturing a rotary converter to run as high as

1,500 volts on the D.C. side, and rotaries giving 750 V. connected four in series would be necessary to maintain the 3,000 volts; this is not an economical proposition. On the other hand, motor generators can be made to give 1,500 volts on one commutator quite satisfactorily, and this would involve only two machines in series.

Motor generators have another advantage, and that is that they do not tend to throw off their load so easily as rotaries when there is a disturbance on the system.

Motor Converter. We now come to a very interesting type of converting plant, which is intermediate between

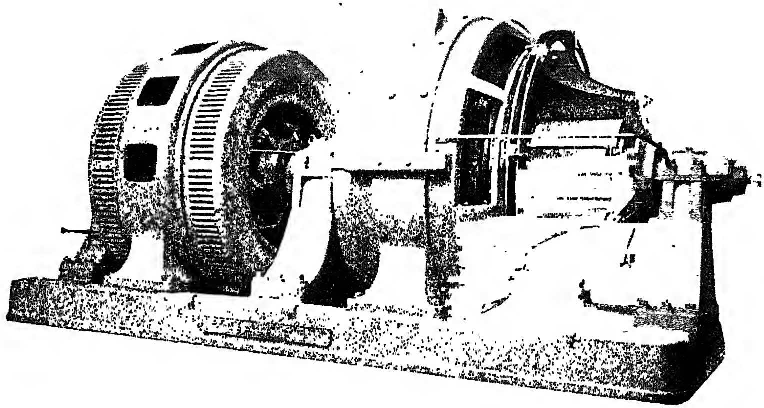


Fig. 44.—2,500 kW. Motor Converter.

the rotary and the motor generator, and which possesses some of the advantages of both. Its efficiency is slightly less than that of the rotary, but considerably higher than that of the motor generator. It is a good deal more stable than the rotary, and where space is of importance, it has a great advantage, as no static transformers are necessary.

The machine (an illustration of which is given in Fig. 44) consists of an induction motor, the stator of which can be wound for the same voltage as an induction motor generator, coupled to a continuous-current machine, which is practically a rotary converter without any slip

rings. The rotor winding is permanently electrically connected to the armature of the D.C. machine at 12 or 24 points, and in the case of three bearing machines these connections are taken through the centre of the shaft.

For the purpose of starting, the rotor is provided with three or six slip rings, by means of which resistances can be inserted between the winding and the star point. The stator and rotor act as primary and secondary of a transformer. Assuming that the machine is running in synchronism, and for simplicity's sake that the A.C. and D.C. ends have the same number of poles (in the diagram two poles), the machine will run at a speed corresponding to half the primary frequency, or what is termed 50 per cent. slip. It follows that the rotating field in the stator rotates relatively to the rotor at a speed corresponding to half the frequency of the supply circuit, and it thus induces in the rotor windings a current which has also half the frequency of the supply circuit.

Now the number of poles at the D.C. end is so arranged that the frequency of the current induced in the armature winding at the speed mentioned is the same as the frequency of the rotor currents, and it is therefore possible to interconnect the rotor and armature windings. When this is done, the speed remains constant, the A.C. and D.C. ends of the set thus connected behaving as a single synchronous machine. As the rotor revolves at a speed corresponding to half the frequency of the supply circuit, only half the electrical energy supplied to the A.C. end is converted into mechanical energy, and transmitted by means of the shaft to the D.C. end. The other half, by the transformer action of the stator and the rotor, is transformed through the rotor winding to the armature winding in the form of electrical energy. Thus the A.C. end operates half as a motor and half as a transformer, while the D.C. end operates half as a continuous-current generator, and half as a rotary converter. A diagram of the connections is shown in Fig. 45.

Number of Poles. It is commonly assumed that in

all cases the motor converter runs at a speed corresponding to one-half of the frequency of supply, and that

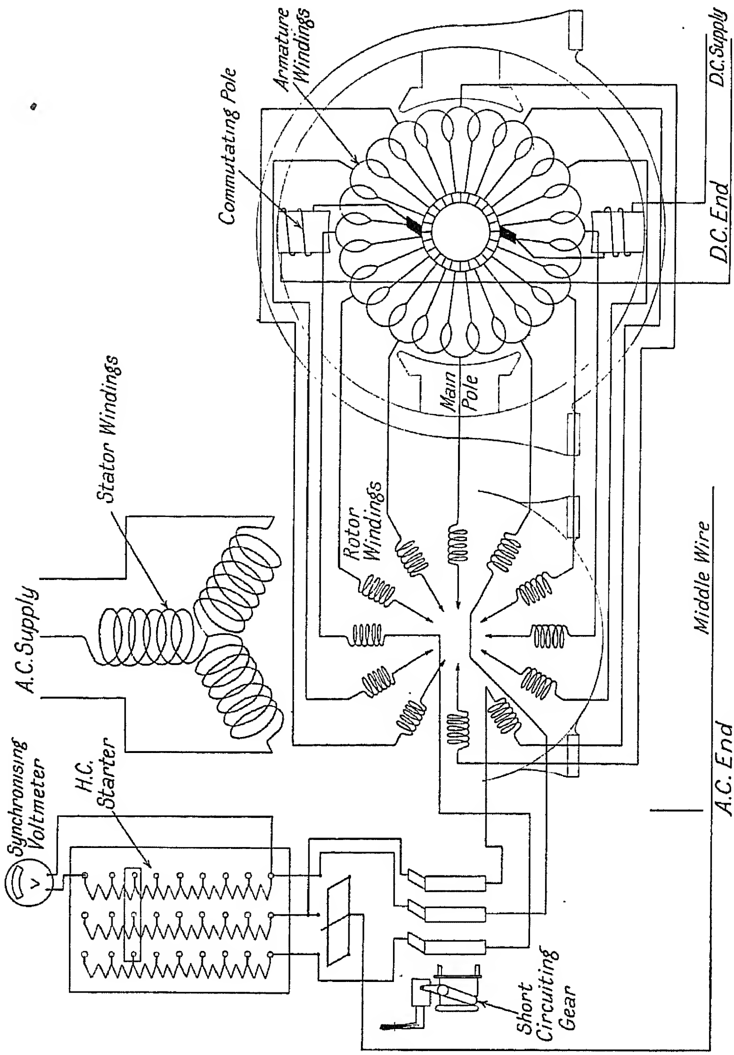


FIG. 45.—Diagram of Connections for Motor Converter.

one-half of the E.H.T. energy supplied to it is transformed into mechanical energy, but this is only true when the

number of poles on the A.C. machine is the same as the number on the D.C. It is not always convenient to have the number of poles the same; but as long as the sum of the number of poles on the A.C. and D.C. end is the same, the speed will be the same.

For example, take a 2,500 kW. motor converter running at 428 revs. converting from 10,000 volts three-phase to 400 volts D.C. This machine may be built with ten D.C. poles and four A.C. poles, or eight D.C. poles and six A.C. poles.

It is quite simple to determine the speed with any particular arrangement of poles.

If M = revs per minute.
C = periods per second of supply circuit.
p_a = number of pairs of poles A.C. end.
p_c = ,, ,, ,, D.C. end.

Then $M = \dfrac{60C}{p_a + p_c}$

Now, the proportion of the total energy converted into mechanical energy is $\dfrac{p_a}{p_a + p_c}$ and the proportion commuted

$$\frac{p_c}{p_a + p_c}$$

If the number of pairs of poles are equal, these proportions are equal, but in the cases mentioned above,

No. 1 Machine,	mechanical	proportion	$\frac{5}{7}$
	electrical	,,	$\frac{2}{7}$
No 2. Machine,	mechanical	,,	$\frac{4}{7}$
	electrical	,,	$\frac{3}{7}$

The starting of a motor converter is a comparatively simple matter. The E.H.T. supply pressure is switched direct on to the stator windings, and this induces current in the rotor, which is limited by means of the resistance connected to the slip rings. The machine starts to rotate, and the D.C. end, which is self-excited, builds up its field. When the machine approaches synchronous speed,

the E.M.F. induced in rotor and armature will alternately be in opposition and conjunction, and consequently the current flowing in the starting resistance will be small and large alternately, causing the needle of the synchronizing voltmeter, which is connected across the starting resistance, to oscillate. The oscillations, however, will gradually become slower, until they become so slow that it is possible to close the switch for short-circuiting the starting resistance, and this is actually done when the needle is falling and is near the zero end of the scale. The short-circuiting device is then closed, connecting all the windings to the star point. This point is the one from which the neutral connection for balancing purposes is taken, and, of course, the out-of-balance current has to come through the brushes on the slip rings.

Another method of starting, which is quicker and practically self-synchronizing, is to run up the machine until it is slightly above synchronous speed, and then by means of the change-over switch, to connect choking coils across the slip rings in place of the resistances. When this is done the speed falls, and when the machine reaches synchronous speed, the choking coils hold it in synchronism, and the switch short-circuiting the slip rings can be closed. By this method we can get a 2,500 kW. machine from rest to supply in under one minute.

Mercury Arc Rectifier

About twenty-four years ago, Cooper Hewitt noticed that a mercury arc in high vacua had the peculiar property of permitting the passage of current in one direction only, that is to say the current is intercepted at each half-period, the positive half-waves only passing between the two electrodes. This arrangement constitutes what may be described as an electric valve. This valve action is not the peculiar property of mercury, but is merely due to the arrangement of two electrodes, whereby one (the cathode) is brought to a state of electronic emission, and the other (the anode) is maintained at a temperature

below that at which the formation of electrons is possible. In the commercial rectifier, mercury is used because its vapour can be readily condensed, and led back to the cathode without loss.

If we take the simplest case of a single-phase circuit, we use the positive half of the wave only with a gap between, Fig. 46. This means a very intermittent direct current, and it only utilizes half the power of the alternating supply. We must therefore bring in the negative half of the wave and give it a positive sense, with regard to the D.C. current. This is done by connecting in the manner shown in Fig. 47, which represents a divided secondary, the mid-point of which is brought out, and forms the negative pole of the direct-current system, the cathode forming the positive pole. Consider the positive half wave—current flowing towards anode—other half inactive, after the wave has passed through zero, the other half becomes positive and first half inactive. By inserting reactance the wave is prolonged, and prevented from dropping to zero. By making this reactance large enough, it is possible to so reduce the undulations in the rectified wave that even a single-phase primary supply can be satisfactorily converted and commercially used.

The best results, however, are obtained when the primary supply is three-phase, and in this case we have three anodes and one cathode. The rectified current then becomes as shown in Fig. 48.

If we now connect the secondary of a three-phase transformer so as to form a six-phase circuit, we have a still nearer approximation to direct current, and the rectified current is as shown in Fig. 49. Fig. 50 shows that by connecting the transformer so as to form a twelve-phase circuit a still nearer approximation to a direct current is obtained, but difficulties arise with this connection and for practical purposes the six-phase circuit is adopted.

Glass Bulb Type. The simplest form of mercury arc rectifier is the glass-bulb type shown in Fig. 51. This

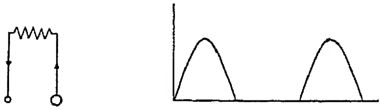


FIG. 46.
Single Phase.

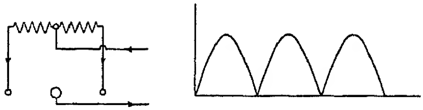


FIG. 47.
Single Phase
with
Divided Secondary.

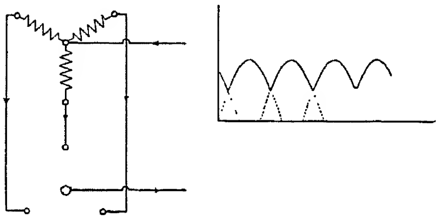


FIG. 48.
Three Phase.

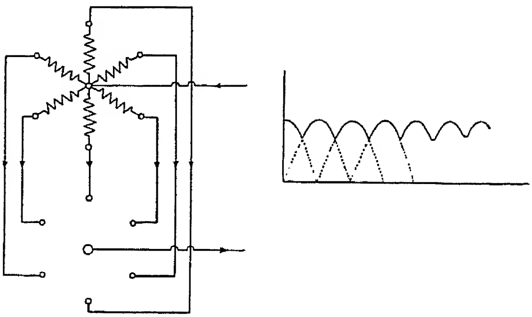


FIG. 49.
Six Phase.

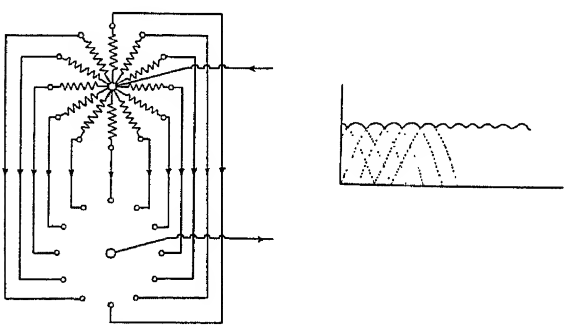


FIG. 50.
Twelve Phase.

is for a three-phase circuit and has three anodes, the cathode being at the bottom. A small auxiliary electrode is also shown at the bottom, and this pocket and the cathode pocket contain mercury. In circuit with the auxiliary electrode is a starting resistance, which is connected to one part of the transformer. By tilting the bulb, the mercury flows from the one pocket to the other, and makes the circuit through the resistance. When the bulb is restored to its normal position, the mercury circuit is broken, and an arc is formed at the break, which vaporizes sufficient mercury to allow the main arc to pass from the anodes to the cathode, and once this arc is started, full load may be put on the rectifier. Regulation is obtained by varying the tapping on the transformer, which of course alters the applied A.C. voltage on the rectifier, and the D.C. voltage varies accordingly.

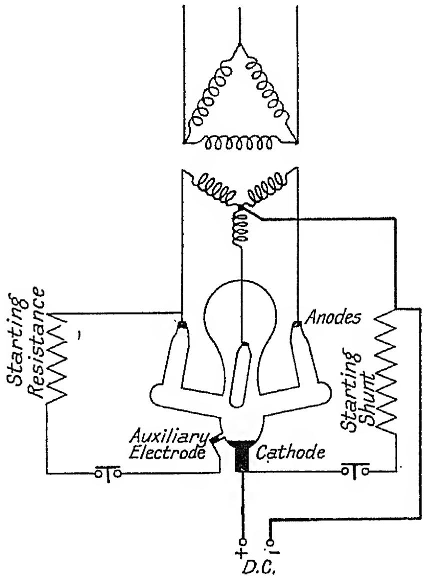


Fig. 51.—Glass Bulb Type Mercury Arc Rectifier.

This type of rectifier is very useful for boosting up a distant part of the network where the pressure is low, and where the current required is not large, but where greater power is necessary the Brown Boveri Rectifier is used.

Brown Boveri Steel Cylinder Type. This (as shown in Fig. 52) consists of a large welded steel cylinder (the arc chamber) and a narrow cylinder (the condensing chamber) mounted above, the two being connected by a heavy anode plate to which the anodes are fixed. The

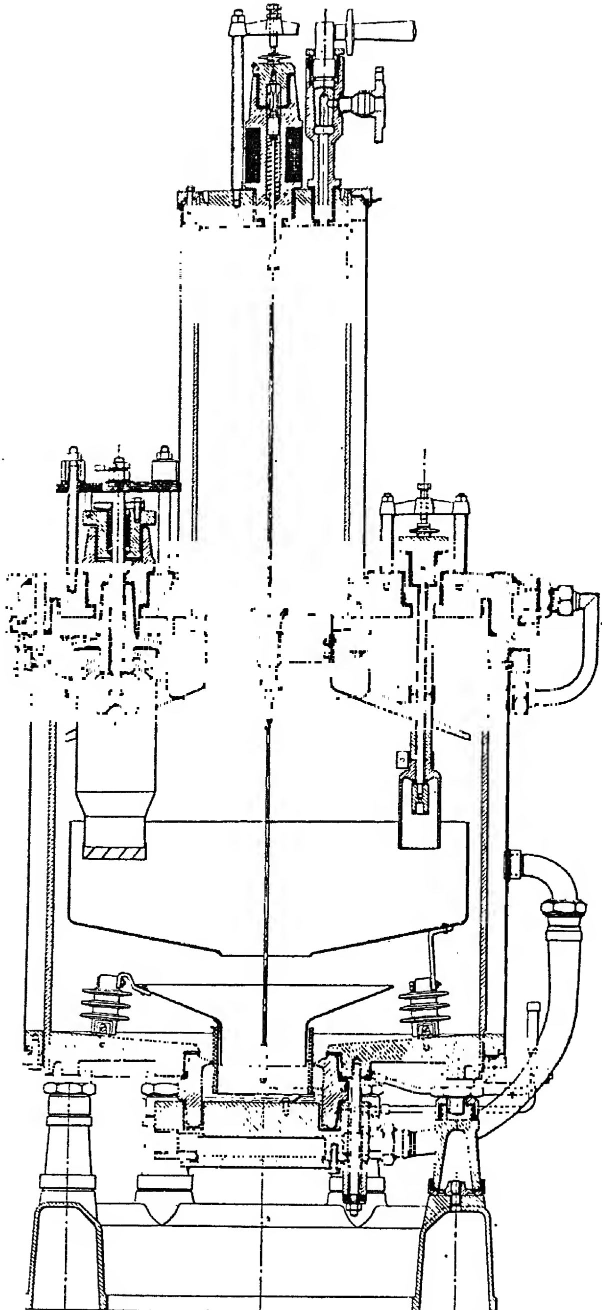


Fig. 52.—Brown Boveri Steel-Cased Mercury Arc Rectifier.

bottom of the arc chamber is closed in by a plate, in the centre of which is the cathode, while the top of the condensing cylinder is closed by a plate carrying the ignition coil. The whole rectifier is mounted on porcelain insulators which insulate it from earth.

There are six main anodes and two auxiliary anodes, placed in a circle round the anode plate. The auxiliary anodes serve to maintain the arc when the load drops to a very low level on account of the main arc having a tendency to become unstable under such conditions. This auxiliary circuit is kept going by a small exciting transformer (about 1 kW.), and the current is kept down by a resistance as in the other case. The current in the auxiliary circuit is used entirely for forming an arc, which keeps up the temperature of the cathode spot. Both cylinders are water-cooled, and the anodes also in the older type.

The ignition of the arc is accomplished by an ignition anode, which, when the main transformer is switched on, is by means of the ignition coil forced into contact with the pool of mercury at the cathode. The current that flows causes the electrode to be withdrawn, thus striking an arc and causing the main arc to start.

Starting. The starting is very simple: (1) check vacuum and start up vacuum pump if necessary; (2) turn on cooling water; (3) close E.H.T. switch, and within a second or two the rectifier is ready to take load, the next operation being to close the D.C. switch and put the plant on supply.

With this apparatus, D.C. pressure up to 6,000 volts can be obtained from a single unit. The capacity for momentary overload is stated to be very great, there being no sparking at the brushes to contend with. For example, in a rectifier giving normally 1,800 volts, 400 amp. D.C., the current reached 8,700 amps. before the switch cleared, or about twenty-two times full load current. Sixty similar short circuits were applied during two days. The rectifier was then opened up, but was found to be in precisely the same condition as when sealed up before the tests.

Efficiency. One valuable point about the mercury arc rectifier is that its efficiency remains practically constant at all loads. This is due to the fact that the drop of pressure in the arc is approximately constant under all load and pressure conditions: it varies roughly between 20/25 volts.

This constant pressure drop makes it clear that the rectifier is not of much use at pressures below 400 volts, as its efficiency does not compare with other types of converting plant, but conversely it scores very heavily when we get to pressures of 1,000 volts and over. Assuming that the drop of pressure in the arc is the only loss—

25 volts out of	100 leaves	75.	75 per cent. efficiency at 100 V.
25 ,, ,,	,, 1,000 ,,	975.	97·5 per cent. efficiency at 1,000 V.
25 ,, ,,	,, 3,000 ,,	2975.	99 per cent. at 3,000 V.

It is stated that one equipment is now in operation on a railway load, 4,000 volts D.C. 800 kW., and that a single cylinder has been run for twenty-four hours at 5,400 volts, 300 amps. 1,620 kW.

The advantages claimed for mercury arc rectifiers are:

(1) Efficiency high over whole working range.

(2) Simple operation and minimum attention.

(3) No synchronizing.

(4) Very high momentary overload capacity and insensibility to short circuits.

(5) Negligible maintenance.

(6) Low weight, no special foundations.

(7) Noiseless and vibrationless.

At the present time, over 500,000 kW. of rectifiers has been installed, a large proportion of which is automatically controlled. One order for railway work on the Continent is for 95–1,200 kW. remote controlled power rectifier installations.

Regulation. This, perhaps, is the weakest point in the mercury arc rectifier. The only means of varying the pressure on the D.C. terminals is by varying the A.C.

pressure supplied to the rectifier, and this can only be done in two ways: (1) by the use of supplementary transformer tappings; (2) by inserting an induction regulator between the transformer and the rectifier.

The first of these methods, except in the case of very small glass-bulb rectifiers, is not easy to accomplish, as it involves the use of elaborate switching gear, to avoid sparking at the contacts, and the regulation is of necessity very coarse. The second is not open to this objection, as the regulation can be as fine as one could wish; but the induction regulator is very costly, and its introduction affects the efficiency quite considerably.

Compounding. The automatic compensation for drop of voltage when the load comes on, which in the rotary converter is done by compounding in the machine itself, cannot be done in the rectifier without introducing additional auxiliaries with a substantial increase of cost and some loss in efficiency.

Third-Wire Operation. This is not possible on a rectifier, and if required to run on a three-wire system, two rectifiers must be used of half the total voltage. This increases the cost and lowers the efficiency.

Power Factor. The power factor of a mercury arc rectifier can never reach unity, and in fact it does not exceed 92 per cent., which means that the supply system has to furnish approximately 45 per cent. of lagging current to each equipment.

Rotary converters, on the other hand, can be run at unity power factor, or even draw about 20 per cent. leading current, so that for every 1,000 kW. of rectifiers installed, the supply system has to provide 650 kVA. of wattless current extra to what would be required if rotary converters were installed instead. This, of course, is a serious drawback on systems which already have a low power factor.

Rectifier Transformers. Owing to the fact that direct current is taken from only one or two anodes at any one instant, and that the current waves on primary and

secondary depart very materially from a sine wave, the material is less effectively used, and the losses are greater in transformers for rectifiers than is the case with transformers used for rotaries. As a result, rectifier transformers are about 55 per cent. larger and heavier than rotary transformers.

Undulations on D.C. Voltage. As already pointed out, it is not commercially possible to make rectifiers

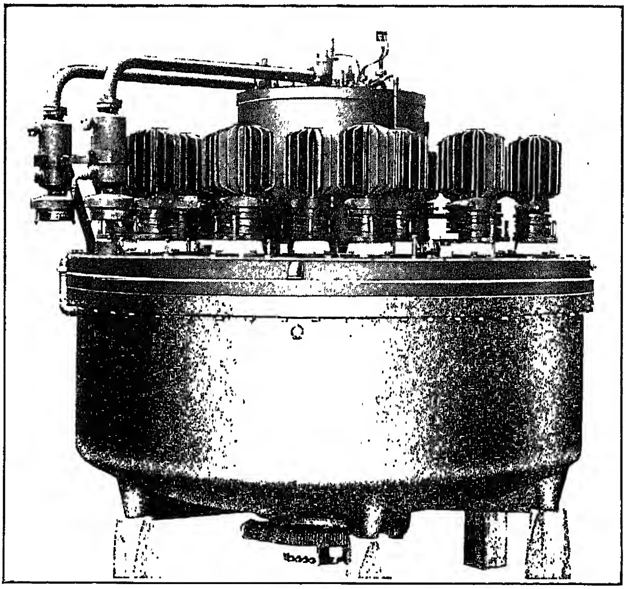


FIG. 53.—Mercury Arc Rectifier for an output of 16,000 amperes at 300 volts.

to work on more than six phases (equivalent to a six-part commutator), and the undulations on the D.C. side are therefore much greater than with a rotary, and may, under certain circumstances, be troublesome. These undulations can be considerably reduced by the insertion of reactance in the D.C. side, but this of course means more expense, and slightly less efficiency.

Fig. 53 shows a modern type of Brown Boveri steel cylinder type mercury arc rectifier, having an output of

16,000 amperes at 300 volts. This is an exceptionally large current to obtain from one unit; but of course the efficiency will be low.

Recent Developments. The author has been informed that rectifiers have now been constructed to give 16,000 amps. at 300 volts, and one of these has been tested to 20,000 amps. In New York, where the voltage is 230, one of these 16,000 amp. rectifiers has been installed. The efficiency, of course, is a great deal lower than that of other types of converting plant, but the difficulty of finding room and the necessity for noiseless running are in this particular case overriding considerations.

Backfiring has in the past caused a good deal of trouble with mercury arc rectifiers, and it is interesting to note that the manufacturers now incorporate in their latest design a backfire protection, which consists of a very simple fitting mounted inside the rectifiers, and which has had most beneficial results. The effect of the new fitting is such that, generally speaking, higher overloads can be taken, and furthermore it is sometimes possible to increase the normal rating of the rectifier itself.

The problem of regulation of mercury arc rectifiers has recently been tackled by the manufacturers, and a step switch which moves over contacts connected to a regulator winding, which is connected in the E.H.T. side of the transformer, is used for this purpose. The makers claim that this is a satisfactory solution of the problem of regulation, but of course one cannot get the fine regulation that is possible in a rotating converter, as the difficulty of dealing with a large number of tappings in the E.H.T. side is very great.

These step switches have been made for voltages of 37,000, and the automatic control of the mercury arc rectifier, is rendered possible by their use.

Synchronous Condensers

A great deal has been written on the improvement of power factor, and, with the very large schemes that are now being installed, which in many cases cover a

large area, and necessitate long transmission lines, the importance of this subject has greatly increased. The two types of apparatus which are mainly used to attain this end are the static condenser and the synchronous condenser, and it is with the latter type, and the substations in which they are installed, that the author proposes to deal.

The synchronous condenser is practically a synchronous motor, with arrangements for varying the field in small steps. The stator is wound in the usual way, special care being taken with the insulation and the bracing of the coils, to prevent any movement under the magnetic forces produced by fault conditions.

The rotor, or revolving field, is similar to that used in a synchronous motor, and is provided with damping coils. The D.C. current for the rotor is obtained from an exciter mounted on the end of the shaft. When the machine is running with the normal field, that is the field current which with the machine running at synchronous speed will give the same E.H.T. pressure on the terminal as the supply pressure, the synchronous condenser will merely take sufficient E.H.T. current to overcome the friction and other losses, and the machine will not be doing any power factor correcting. A variation, however, of the field above or below the normal will increase or lower the terminal volts on the condenser, and cause it to take a leading or lagging current up to the full extent of the capacity of the machine, with a beneficial effect upon the power factor of the whole system.

The advantages to be obtained by the installation of synchronous condensers is illustrated in the table given opposite, for which, and for other details in connection with synchronous condensers, the author is indebted to an article by Mr. E. M. Johnson in the Metropolitan Vickers *Gazette* for June and July 1927.

These advantages are so considerable that engineers are prepared to spend very large sums of money in providing synchronous condensers, being convinced that they are saving money by so doing. As an example of the enormous size to which these machines are attaining,

	System Voltage.	Voltage Charac-teristic.	Load Delivered kW.	Capitalized Transmission Costs per kW Delivered.	Power Factor of Generators per cent.
				£ s. d.	
Without condenser	110,000	Variable	10,500	20 10 0	75
With condenser .	110,000	Constant	27,500	17 10 0	97·5
Without condenser	33,000	Variable	2,145	15 10 0	70
With condenser .	33,000	Constant	6,000	10 10 0	99

the following particulars, taken from the *General Electrical Review* for January, 1927, will be of interest :

"Three 50,000 kVA. 600 r.p.m. 50-cycle synchronous condensers were under construction for the Southern California Edison Company. They will be not only the largest machines of their type, but will have higher efficiencies than have heretofore been secured with this class of apparatus, the total calculated losses being only one and two-thirds per cent.

"They are to be utilized for voltage regulation at the receiving end of the 220,000-volt Big Creek lines. They will have a net unit weight of over 380,000 lb. and will be provided with a closed system of ventilation similar to that used on large turbine and waterwheel generators. This method of cooling has been applied to some relatively small condensers, but this will be its first application to machines of record size."

Synchronous condensers have to be run practically continuously; their use is purely economic; they do not generate any current, and it is therefore of very great importance that the losses should be kept to an absolute minimum. This is obtained to some extent by running at a high speed, and incidentally this decreases the capital cost. Fig. 54 shows the losses in kW. as a percentage of the kVA. rating in some Metropolitan Vickers condensers for various outputs up to 30,000 kVA.

Synchronous condensers can be started up by means of a reduced voltage applied to the stator windings, or by means of a special starting motor on the shaft. The

control is quite simple, and can be either manual, semi-automatic, or fully automatic.

In many cases of supply to large consumers where the loads are somewhat scattered, a specially favourable tariff is given to a consumer if he will maintain a high-power factor, and in this case it pays the consumer to

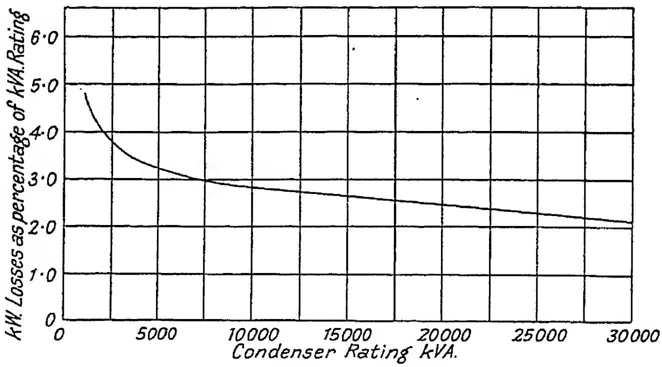


FIG. 54.—Curve showing losses in Synchronous Condensers as a percentage of kVA. rating.

instal an automatic synchronous condenser, as the saving on the tariff more than pays for the capital cost of the condenser and its losses while running. In other cases, the Supply Co. themselves find it profitable to instal synchronous condensers at certain parts of their system, and thus increase the amount of power that can be transmitted by the existing cables.

CHAPTER VII

EFFICIENCY AND STABILITY

In making a choice of plant for a substation, the relative importance of efficiency and stability have to be weighed up very carefully.

Efficiency. If the E.H.T. supply is being taken from a Bulk Supply Co., the price will vary with the maximum demand, and clearly the less efficient plant will increase the maximum demand, and the number of E.H.T. units used for a given output on the D.C. side will be greater. On the other hand, if the more efficient plant is more costly, the interest on the difference between the capital costs in the two cases will have to be considered.

Another point of importance is the floor space occupied by the plant for a given D.C. output, as plant which occupies a large floor space, will require a larger building to accommodate it, and this will increase the capital cost. If the substations already exist, a smaller capacity of the bulky plant can be got into them, and this may, when the load grows, necessitate the building of another substation, or the enlarging of the existing one, all of which will again increase the capital cost.

Reliability and freedom from breakdown are also desirable, as costly repairs and constant attention necessitated by faulty design, all increase the cost per unit.

Stability. This, the author suggests, is distinct from reliability, and is one of the most important, if not the most important characteristic of modern converting plant. It may be defined as the power of continuing to give service under the most adverse conditions that may arise in

practice, such as short circuits on the E.H.T. mains, short circuits on the L.T. mains, low steam pressure at the generating station resulting in reduced speed, fluctuating periodicity due to faulty action of governors on steam turbines, etc.

Too much importance cannot be attached to the point of stability, as one may have highly efficient plant at all the substations, but if the plant is liable to throw off its load directly anything untoward happens, the resultant shut down of supply, apart from the question of loss of units, will have a very bad effect on the prestige of the company supplying, and if it happens often, will raise questions of compensation for losses due to machinery lying idle and general stoppage of work.

The most stable plant of all is of course the storage battery, and in the case of a comparatively small supply system, the most efficient plant might be installed in conjunction with storage batteries, although this plant might be the least stable of the types available.

However, as pointed out in another part of the book (Chap. VIII), owing to the increase in load generally, it is impossible in most cases to provide the money or the space necessary for a storage battery capable of keeping the supply going, except for a few minutes, and we are therefore thrown back upon the choice of converting plant when considering the question of stability.

Comparison of Efficiency and Stability of Various Types of Converting Plant. At the present moment, there is no one piece of apparatus which will convert in one operation from E.H.T. three-phase, to L.T., D.C., and in this respect D.C. distribution is at a disadvantage as compared with A.C. distribution, where one piece of apparatus, the static transformer, can take a current, say at 11,000 volts, and deliver current on the L.T. side at 200 and 400 volts, which is suitable for the consumer.

In every case with A.C. to D.C. converters, two machines or pieces of apparatus are required. In the case of the motor generator, we have an A.C. motor which absorbs all the E.H.T. A.C. current supplied, and transforms it

into mechanical power, which power is communicated through the shaft to the D.C. generator. The rotary converter cannot deal with the E.H.T. current direct, and therefore requires the interposition of a static transformer, which reduces the whole of the E.H.T. A.C. current to L.T. A.C. current at a suitable voltage for the rotary to convert.

The motor converter consists of two machines, an A.C. motor (the stator and rotor of which also act as a transformer), which converts part of the E.H.T. A.C. current supplied to it into mechanical power which is conveyed through the shaft to the D.C. generator. The rest of the E.H.T. A.C. current is transformed to a suitable voltage, and by the rotary converter action of the D.C. generator, is converted to the same D.C. voltage as is generated by itself. The mercury arc rectifier, in the same way as the rotary converter, requires that the pressure be reduced by a static transformer to that suitable for the D.C. supply.

The highest efficiency possible, compatible with a reasonable amount of stability, should be aimed at, and the converters must be capable of standing severe short circuits without danger. The standard specification for converting plant states a guaranteed efficiency subject to a tolerance of $\frac{3}{4}$ per cent. and a rejection limit of $1\frac{1}{2}$ per cent. inclusive of the tolerance. This means that the buyer cannot reject the machine unless it is $1\frac{1}{2}$ per cent. below the specified figure. This is rather a serious matter, as the continuous loss due to the machine being $1\frac{1}{2}$ per cent. less efficient than the guarantee is very considerable.

A case which the author has recently investigated of two large machines purchased from two manufacturers to the same specification, showed a difference of 1·9 per cent. at full load, 2·5 per cent. at three-quarter load, and 2·8 per cent. at half load. A calculation brought out the rather startling fact that in a year's working, the less efficient machine would require to be supplied with over 100,000 more E.H.T. units than the other, the D.C. output in both cases being exactly the same. The less

efficient of the two machines was within the tolerance limit.

The author is of the opinion that a system of bonuses and penalties should be embodied in the specification, that is to say, for every 0·5 per cent. above the guarantee an additional sum should be paid, and for every 0·5 per cent. below the tolerance limit, a sum should be deducted from the price of the machine. The guaranteed figure to be the full load or the average load figure; the average figure to be obtained by taking four times the full load figure, three times the three-quarter load figure, and twice the half load figure, summing all these up and dividing by nine.

The purchaser could well afford to pay something extra for a machine which gives him more than he has asked for and calculated on, because he will save a definite amount in each unit turned out, and conversely, if the efficiency is below his figure, he will lose a definite amount in each unit turned out, and is therefore entitled to be compensated.

Differences in Efficiency. Now, although all these types of converting plant require two pieces of apparatus to convert from A.C. to D.C. the difference in efficiency is very considerable, varying with the D.C. voltage required and the type of converting plant, the extremes being a motor generator converting from E.H.T. to 100 V. three-wire D.C., and a rectifier, converting from E.H.T. to 3,000 volts D.C. If we take as a unit for comparison converting plant of 1,000 kW. to 1,500 kW., we see that in the first case the efficiency is 88 per cent., and in the second case about 98 per cent. It is only fair to point out, however, that if the rectifier is used for converting E.H.T. to 100 volts D.C., the efficiency would be below 80 per cent.

The most efficient machine for 200 volt D.C. conversion is the rotary converter, the efficiency for 1,500 kW. sets being 93 per cent. The efficiency of the motor converter would be about 91·0 per cent.

Coming now to a D.C. voltage of 500 (250 volts a side),

we find that the efficiencies—always remembering that two rectifiers of 250 volts each are required—are as follows :

Rotary Converter . . .	94 per cent.
Motor Converter . . .	92·5 per cent.
Rectifier	89 per cent.
Motor Generator . . .	90 per cent.

Stability. Undoubtedly, the most suitable type of converting plant is the motor generator, the chief reason for its stability being the fact that the D.C. voltage and output is not dependent upon the A.C. voltage as long as the periodicity remains the same. The E.H.T. voltage may drop to 50 per cent. of normal, but if the frequency remains constant, the speed of the machine will not vary, and consequently the D.C. voltage will remain unchanged. Of course, the current taken by the A.C. motor will vary inversely as the A.C. pressure. That is to say, if the pressure drops to 50 per cent. of normal, the A.C. current will be doubled, but as this presumably is only the case for a short period, no damage should be done to the A.C. motor. Again, if there is a slight variation in the speed of the turbine at the generating station, the motor generator will follow this variation of speed, and the effect upon the D.C. volts will only be to the extent of the variation in speed. In all other types of converting plant, the D.C. voltage is directly affected by a variation in the A.C. volts, even although the speed remains constant.

In the case of the rotary converter and the mercury arc rectifier, this variation of the D.C. volts is directly proportional to the variation in the A.C. volts, but in the motor converter, which is intermediate between a rotary converter and a motor generator, the variation in the D.C. voltage, if the periodicity remains constant, is less than the variation in the A.C. volts.

For the reasons above stated, it seems clear, therefore, that converting plant may be divided into three classes as far as stability is concerned :

1. Motor Generators.
2. Motor Converters.

3. Rotary Converters and Mercury Arc Rectifiers.

Unfortunately, the motor generator, although the most stable type, is the least efficient, and in fact if the plant is classified according to efficiency, the above table would be reversed. We are therefore bound to make a compromise between the most efficient and the most stable machine, and in the author's experience, a great deal can be said for the motor converter.

Advantages of Motor Converters.

(1) **Reliability under Breakdown Conditions.** This is of vital importance, as a machine which will hang on to the load when there is a disturbance on the E.H.T. system is very valuable. It is only inferior to the motor generator in this respect.

(2) **Small Floor Space Occupied.** Owing to the difficulty in getting suitable premises in the centre of a large town, this is becoming more and more important. A rotary converter with single-phase transformers requires twice the ground-floor area, and with a three-phase transformer one and a half times the area that is necessary for a motor converter.

A motor generator arranged for three-wire supply, *i.e.* one generator each side of the motor, will occupy about one and a half times the floor area required for a motor converter, and a mercury arc rectifier would take about the same.

(3) **Fire Danger, due to presence of large quantities of Oil in Transformer, eliminated.** These transformers are necessary in the case of rotary converters and rectifiers, but are not required with motor generators and motor converters. There is a considerable difference of opinion as to the danger from the oil in these transformers, but one very serious disaster occurred in London some years ago, due to oil leakage, and it must be reckoned with as a possibility.

(4) **Absence of Slip Ring Troubles.** The comparison here is only with the rotary converter. It is true that

motor converters have slip rings, but they carry very little current and give no trouble; whereas with rotaries, very large currents, in fact, the whole of the L.T.-A.C. current, has to be carried through the slip rings, and the grinding of these rings and renewal of brushes is quite an item to be considered.

(5) **Wide Range of Voltage Variation.** Rotary converters will deal with the ordinary variation of pressure, provided the frequency is kept constant; but if for any reason the sets at the generating station run fast or slow, there is a difficulty in getting the load out of the rotaries, and also in getting them in and out of circuit. The motor converter is not limited in this way, as owing to the fact that it works half as a generator its range of regulation is almost double that of the rotary. Motor generators are as good as motor converters for regulation, but mercury arc rectifiers have no regulation at all, unless an induction regulator is interposed, and this increases the capital cost and reduces the efficiency.

The Disadvantages of Motor Converters.

(1) **The E.H.T. Winding.** The E.H.T. winding is direct on the machine, instead of, in the case of rotary converters and rectifiers, immersed in oil in the transformer. If the winding breaks down, the machine is out of commission for some considerable time, whereas in the case of rotaries and rectifiers, if single-phase transformers are used, the unit is only off supply for the time necessary to change the faulty single-phase transformer for a spare, a matter of a few hours.

The motor generator shares this disadvantage with the motor converter, but with modern methods of winding the danger of a breakdown of the E.H.T. winding in a motor converter is rather remote.

(2) **The Efficiency is less than the Rotary.** The difference with large units is about 1 per cent.; but as the motor converter maintains its efficiency better at three-quarter and half load, the difference in a year's

working becomes less. The difference is again reduced by the losses between the transformers and the rotary converter, which in some cases in the author's experience, amounts to 1 per cent. In addition, the capital cost of putting in these cables in the case of a 1,500-kW. rotary, amounted to between £500 and £600, none of which expense is entailed in the case of the motor converter, as the leads between the induction motor are taken through the shaft, and form part of the machine. The mercury arc rectifier is a good deal higher in efficiency at a voltage of 1,000 or over, but at 400 it is slightly less efficient than a motor converter, and at 200 volts considerably less.

In the preceding pages the author has put forward the advantages and disadvantages of the motor converter, and in doing so has also brought out the advantages and disadvantages of the other types of converting plant. There is need for all these types, and each case should be considered on its own merits.

For a Supply of 3,000 Volts D.C. the mercury arc rectifier scores heavily, as not only is its efficiency very high, but one rectifier will give the 3,000 volts.

The motor generator with two generators, one each side of the motor, is the only alternative type that can be used at the present day, although, as previously mentioned, the author does not see why the motor converter should not be made for 1,500 volts. This voltage, of course, is only employed on large traction systems covering a wide range of country.

At 1,500 Volts (which is also only used for traction purposes) the rotary converter comes into the field, two machines, each giving 750 volts, being used. The 1,500-volt motor converter is also to be reckoned with. The rectifier still leads in efficiency at this voltage.

At 600 Volts, which is used largely for suburban traffic, all types of plant can be used, and the determination as to which is the most suitable is very difficult. There is nothing much between the efficiencies of rectifier, rotary, or motor converter.

At 400 and 500 Volts, for supplying light and power to towns where a three-wire system is employed the choice is between the rotary converter and the motor converter. The motor generator is too low in efficiency and the mercury arc rectifier, owing to the fact that two rectifiers must be run, each giving either 200 or 250 volts, is also much lower in efficiency than the rotary or motor converter.

CHAPTER VIII

STORAGE BATTERIES

It must be admitted to the credit of the early designers of storage batteries of the stationary type that, in spite of much research and investigation, no improvement of outstanding importance has been discovered during the last few years.

Very considerable advance in the design has been made for batteries for special purposes such as electric vehicles, submarines and other special services, but in the main the present-day stationary batteries are identical with those produced a number of years ago. Batteries have however been brought to a state of greater reliability, strength and uniformity, owing to careful investigations in many directions. For example, it has been found that even minute variations in the physical properties of the materials used have an important effect on the plate, even when the chemical properties are identical. By paying great attention to details of this kind, selecting the most suitable materials for the particular service for which they are required, and eliminating the weak points in earlier designs, batteries of reliable make can now be depended upon to fulfil the most onerous conditions of service with very satisfactory life and low maintenance charges.

Uses of Battery: Taking the Peak Load. In the earlier days of electrical supply, the storage battery was looked upon as a means of maintaining the whole supply for, say, one hour, when a failure occurred on the converting plant in a substation, or there was a cessation of supply

from the generating station. It was also installed for the purpose of levelling the load of the generating station, by taking off the peak load every day for an hour or so, thus enabling the generating station to run at a very nearly constant load all day.

Several very excellent papers have been written on this subject, and they still have some application to those cases where the supply is a small one and cannot increase very much; but in the great majority of cases the load has grown so rapidly that it is no longer possible to provide and maintain a battery which will be capable of taking the whole supply for one hour, or even half an hour. This is impossible, first of all because the cost of such a battery would be prohibitive, and, secondly, because it would not be possible, in an ordinary substation, to find the room to house it.

Emergency Stand-by. The storage battery, therefore, at any rate in case of a supply to a large town, must be looked upon as a means of maintaining the supply for, say, ten minutes or fifteen minutes, which time would be sufficient to start up other plant in substation and generating station. The occasions on which this would be necessary are a sudden fog or breakdown of the generating plant.

It is also very useful for maintaining the whole supply at night, or at times of light load, thus enabling the running machinery to be shut down, and the necessary overhauling and cleaning done. The storage battery is also invaluable in the time of a complete shut down, in keeping the lighting and other necessary auxiliaries going. In order to maintain the whole supply for even ten minutes or fifteen minutes, a very large battery is required in some cases. For example, in Detroit, the peak load during the winter was 55,000 amps. at 134 volts on each side of a three-wire system and the four batteries installed were capable of carrying this load for fourteen minutes. In another case, one battery alone has a capacity of 25,000 amps. at 110 volts for one hour, or 80,000 for ten minutes.

A large storage battery in this country is specified to give the following outputs at 220 volts :

Amperes.	Hours or Minutes.	Minimum Volts per cell.	Ampere Hours.
1,200	10 hours	1·8	12,000
2,000	5 ,,	1·78	10,000
3,750	2 ,,	1·7	7,500
6,000	1 ,,	1·65	6,000
8,000	35 minutes	—	4,660
15,000	For a few minutes	—	—

From the above figures, it is seen that some companies are prepared to instal very large batteries at a very considerable cost in order to maintain supply, but this practice is more a vogue in America than in this country. It is stated that in New York City alone there are batteries with stand-by capacity capable of discharging at over 2,000,000 amps.

Floor Space Required. With regard to the floor space occupied, a battery whose capacity at the one-hour rate is 2,500 kW. will occupy twenty-five to thirty times the space required for a motor converter to give this output continuously. This is on the assumption that the battery is installed on one level; but if erected in two tiers, this figure will be reduced by half.

It is only fair, however, to point out that batteries used for stand-by purposes only will last a very long time, as the life of a battery, speaking generally, varies inversely as the amount of usage, and it really is not necessary to instal a battery which is designed to be discharged to its full capacity regularly. Such a battery would be much heavier, more costly, and would occupy a much larger space than a battery designed for stand-by purposes only.

If battery manufacturers were to realize the fact and bring out a battery which has a very much higher discharge rate for a given weight and a reasonable life,

bearing in mind the comparatively few times it will be called upon to operate, the central station battery might take on a new lease of life. A battery so designed would probably occupy say one quarter to one-sixth of the space of the more substantial type, and the price would be correspondingly reduced. These very large reductions in price and space occupied would be a great attraction to an engineer who set great store on continuity of supply.

Variation of Capacity with Discharge Rate. The figures given above illustrate a point which is not generally appreciated, and that is the variation of capacity with the discharge rate. It will be noticed that the capacity at the one-hour rate is exactly one-half the capacity at the ten-hour rate, and this figure agrees with the author's experience.

One perhaps naturally asks, Is it necessary, in order to bring the battery to a fully charged state after it has been completely discharged, to put the same number of ampere hours into the battery in the case where it is discharged in one hour as is necessary when the discharge is prolonged over ten hours? If this were necessary, the efficiency of the battery at the one-hour rate would be hopeless, but as a matter of fact it is not necessary; and if the battery which has been discharged in one hour is allowed to rest, quite an appreciable output can be obtained from it at a lower discharge rate.

The lower capacity at the high discharge rate is due to polarization, and the effects of this disappear to some extent after a rest.

Points to Consider when Installing Batteries. It is not proposed to go into a detailed description of substation batteries, but there are a few points of importance in connection with the position, erection and ventilation which are worth discussing.

The lead storage battery is the only type which is used for large capacity batteries, and the general construction of this is so well known that it is not necessary to describe it here. The universal practice with regard to large batteries is to construct the boxes of wood with a lead lining, and

it is very necessary to insulate these boxes from earth, by means of porcelain or glass insulators. Some acid is certain to get on the outside of the cells due to the spraying action when the cells are overcharged, and this layer of moisture being in contact with the lead lining at the top of the cell will sometimes cause an arc to form across a dirty insulator, which in the author's experience has caused a fire. It is important, therefore, to make the leakage surface over these insulators as great as possible, and the most modern design is to have the ordinary insulators under the cells resting on a piece of timber, and again to insulate the timber from earth by other insulators.

It is not advisable to instal batteries where the rays of the sun strike direct on the cells, as this will cause excessive evaporation and uneven working.

Ventilation. Ventilation is important, but should not be carried to excess by installing large fans, as a powerful current of air passing continuously over the cells will cause a great deal of the electrolyte to be evaporated; and as the make-up has to be with distilled water, this increases the expense of upkeep.

The replenishing of the cells with distilled water involves a considerable amount of trouble and expense, and one has to arrange for a stock to be kept and for water-carts to be filled from this stock for transportation to the various substations. On arrival at the substation, arrangements have to be made to pump the water to a tank near the top of the building and this necessitates keeping the water-cart for some time outside the substation, a matter which is not always easy to arrange.

Electric Distillers. All this trouble has been entirely eliminated in the case of a large London Company by the installation of electric distillers, which, although of small capacity, are working practically continuously, and thus provide sufficient distilled water for the needs of the battery. These distillers can be arranged on or above the battery room, the distilled water flowing, as produced, into a tank, from whence by flexible rubber pipes it passes into the cells. With the exception of the main-

tenance of the distiller, all labour charges in connection with the production and conveyance of the distilled water are eliminated.

Large Batteries. A number of large batteries have been installed in England, and while American opinion favours the pasted plate type of battery on account of the smaller floor space required, the larger batteries in England are practically all of the Planté type. Although batteries with Planté plates occupy greater floor space, they have many advantages as regards robustness and length of service without attention or renewals. They also have the great advantage that they can be used for regular discharges for levelling peaks or other special services as may be required, whereas pasted plates would rapidly deteriorate if used in this way.

Fig. 55 illustrates a typical Tudor battery recently installed by Liverpool Corporation. The battery consists of 280 cells, the one-hour discharge rate being 8,000 amperes and the half-hour discharge rate being 11,800 amperes at 475 volts. This battery is of course capable of discharging at much higher rates, if necessary, for short periods, the quarter-hour rate being 14,300 amps. and the five-minute rate 15,500 amps.

There are a number of problems in connection with large batteries, such as designing the connecting bars for proper distribution of the current and also supporting the copper connections in a suitable manner owing to the heavy magnetic strains that are set up between adjacent conductors or between conductors and nearby steelwork, when the currents are flowing. Fig. 56 illustrates a three-wire battery recently supplied to Birmingham Corporation. It will be noted from this illustration and from Fig. 55 that massive insulators are utilized and that the copper is locked in position at intervals when necessary, to prevent any possibility of the strips jumping out of the insulators during severe strain conditions.

The usual American practice is to rate batteries on the six-minute discharge rate, but the half-hour rating is a

more useful figure, as unfortunately if real trouble develops the assistance of the battery is generally required for a period greater than six minutes. Naturally batteries of

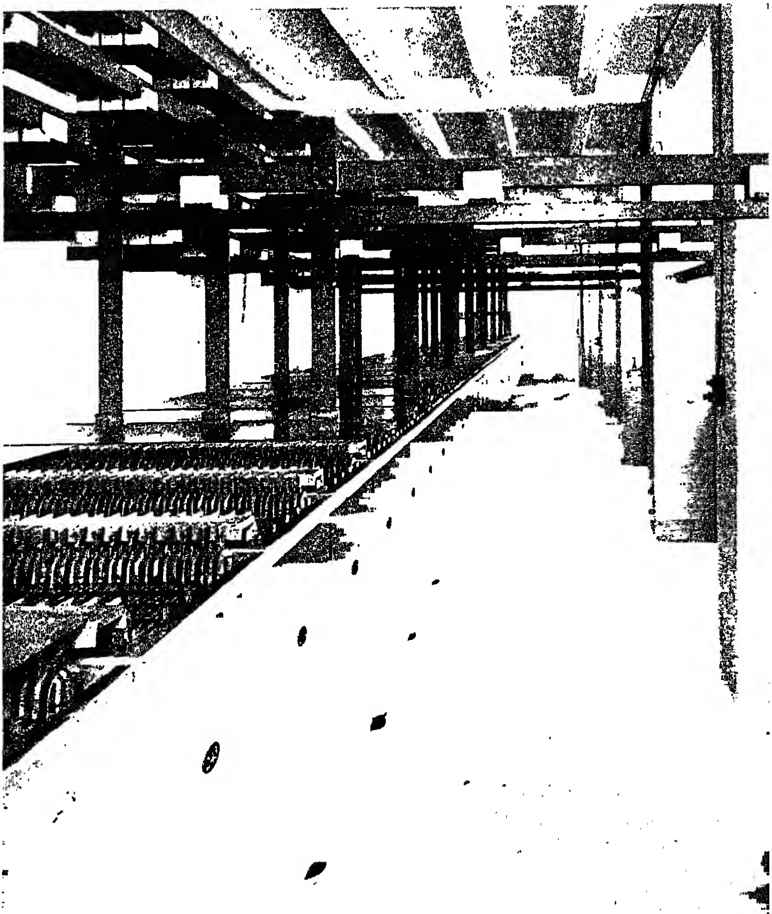


Fig. 55.—Tudor Battery in a Liverpool Station, 280 cells, 8,000 amps. for one hour; 14,300 amps. for fifteen minutes.

this size are capable of giving very heavy currents indeed for short periods, and the limit is practically only governed by the connections and switchgear.

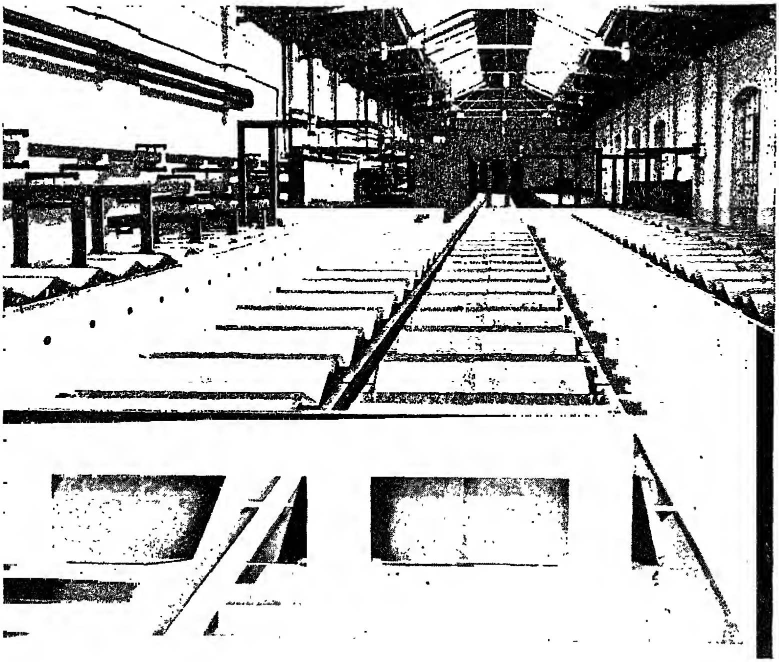


FIG. 56.—Large Battery in Birmingham Corporation Station.

End-Cell Regulators. End-cell switches are almost universally used with large stand-by batteries, as they can then always be floating on the line and full energy is immediately available without any delay whatsoever, and there is no complication as regards possible booster trouble owing to excessive overload. The end-cell switches are remote or automatically controlled, so that additional cells are cut in as the voltage falls and the pressure is maintained at the correct value as long as the necessary capacity is available.

Fig. 57 shows a typical end-cell regulator made by Messrs. Bertram Thomas, suitable for large batteries. These regulators are motor operated and are generally arranged for use with a "Jockey" cell as a lead-saving device. By the use of this "Jockey" cell the number and consequently the cost of copper connections is greatly

reduced, as only half the tappings are taken to the battery which would otherwise be required, *i.e.* the heavy connections are taken to every second cell instead of to each cell. The switch is so arranged that after moving from one main contact or tapping from the battery the "Jockey" cell is next inserted in circuit. The following movement cuts out the "Jockey" cell and the switch brush is then on the next main contact. This cycle is repeated, the

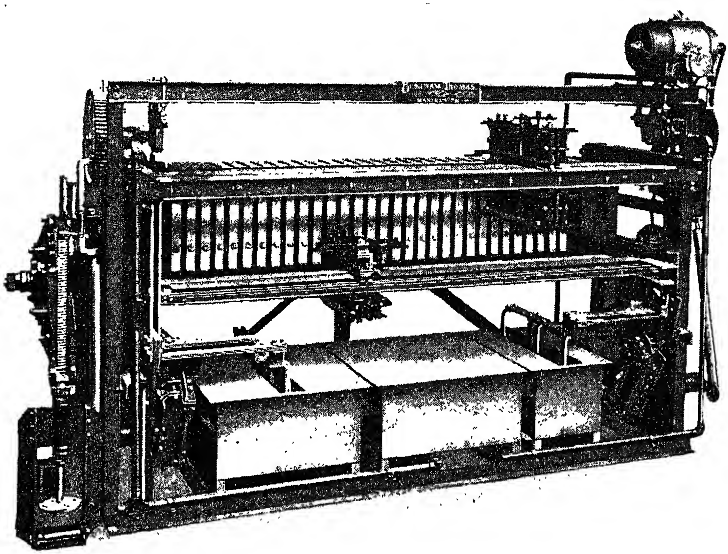


FIG. 57.—End-cell Battery Regulator by Bertram Thomas. Motor driven and arranged for automatic or remote control.

"Jockey" cell being switched in circuit in turn between each main contact. In many cases the actual saving in copper when using a switch with lead-saving device as compared with the full number of tappings is equal to the whole cost of the end-cell regulating switch, or it may be even greater, the saving being naturally dependent upon the distance at which the regulator is fixed from the battery. As these regulators are motor operated and controlled by means of a remote controller from any

convenient controlling point or switchboard as selected by the user, they can be fixed close to the battery or in such a position as will make the aggregate length of the copper connection the shortest possible.

The special controller for operating these regulators can be turned to any desired cell tapping and the regulator will then automatically move to a corresponding position and then stop. This enables the operator to cut-in or cut-out any number of cells as desired by moving the controller arm direct to the required position. The switches are constructed with special spark diverting circuit-breakers arranged in such a manner that the circuit is never made or broken on the main sliding brushes, and, in addition, special indicating flickering lamps are provided and fitted both near the controller and also on the switch itself. These lamps light and flicker during the time the switch is travelling and are only extinguished when the switch comes to rest on the correct position on the contact. All the necessary contactors and auxiliary gear are fitted on the same frame as the regulating switch. A special device is included to slow down the speed of the motor before finally stopping, so that it shall not over-run the proper position on the contact.

The control mechanism is interlocked in such a manner that when an operation has begun the switch must move at least one full contact before it can be started in the opposite direction, so that it is not possible to leave the switch in an incorrect position. These switches can be supplied either of the single- or double-arm pattern.

CHAPTER IX

TRACTION SUBSTATIONS

The war between A.C. and D.C. for traction purposes has been waged for some years, and as there are considerable difficulties from the point of view of interchangeability of rolling stock, and control, in having two different systems, a few years ago a committee was appointed and an inquiry into the whole matter was made. The committee, after a very careful consideration of the matter, recommended that 1,500 D.C. and 3,000 D.C. should be the standard voltages for traction purposes.

Change from A.C. to D.C. A committee appointed by the French Ministry of Public Works some time after the war, also reported in favour of 1,500 V. D.C. with the possibility of using 3,000 volts in exceptional cases. This recommendation was accepted, and 1,500 D.C. has been adopted on the Midi, the Paris-Orléans, and the Paris-Lyons Méditerranée Railways, the three principal electrification schemes in France. The Midi Railway has been running since about 1911 with single-phase current at 16–2/3 periods, and it is significant that this railway company decided to scrap all their A.C. plant and change over to D.C.

The same thing has recently occurred in this country in connection with the Southern Railway, where the London, Brighton & South Coast Section, which has been running for some years single-phase at 6,000 volts, is now to be converted to D.C. at 600 volts, in order to line up with the South Western and South Eastern sections, which are run at 600 volts D.C.

In the United States there is at present no standardiza-

tion, but the Chicago, Milwaukee and St. Paul Railway work at 3,000 volts D.C., and the Illinois Central have decided on 1,500 volts D.C.

The 3,000-V. introduces some difficulties with regard to the converting plant, as it is not possible to construct a rotary converter to give this voltage on one commutator, and, moreover, 1,500 volts is still considered to be too high in rotary converters, if the standard frequency of 50 is adhered to. The trouble on a 50-period system is due to the flashing over from one brush-holder to the other, these brush-holders being necessarily rather close together; but there is no great difficulty in designing rotary converters for 1,500 volts at 25 periods, as the brush-holders can be arranged much further apart.

In the case of the motor converter, as the D.C. end is practically a rotary converter, running at half the periodicity of supply, there should be no difficulty in constructing this type of machine to run at 1,500 volts on a 50-period supply.

High-Speed Circuit-Breaker. Since the introduction of the high-speed circuit-breaker, which cuts out the machine before the short-circuit current has had time to rise to a dangerous value, the prospect of a 1,500-volt rotary converter at 50 periods looks brighter. These high-speed breakers actually break circuit in about 0·01 second, which is less than the time required for a segment of the commutator to pass from one brush-holder to the next, and therefore prevent an arc being drawn out. Relying partly on high speed circuit-breakers and partly on special features of design, some manufacturers have constructed single-armature rotary converters for 50-period supply, giving 1,500 volts on one commutator; but sufficient experience has not yet been obtained to enable any statement as to their reliability to be made.

As it is not an economical proposition, either from the point of view of first cost, running cost or safety, to have to run four machines at 750 volts in series to form one unit, we are thrown back upon the motor generator and the mercury arc rectifier. There is no difficulty in

converting to 3,000 volts on the D.C. side with one rectifier, and in the case of the motor generator the difficulty has been solved by running a synchronous motor driving two generators, one on each side. These machines give 1,500 volts each, and are run permanently in series.

A brief description of the motor generator plant used in the electrification of the South African Railways, where the voltage is 3,000 D.C., and of the mercury arc rectifiers employed in the electrification of the Midi Railway, where the voltage is 1,500 D.C., may be of interest.

The South African Railway Electrification.

This is the first railway electrification scheme to be put into operation in South Africa, and also the *most extensive single installation of automatic substations in the world,* which is in operation. Three-phase power at

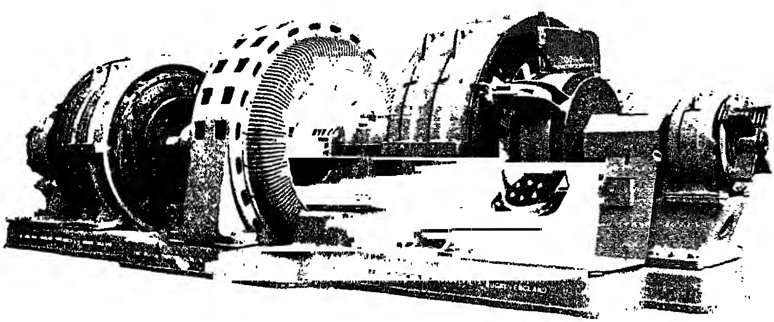


FIG. 58.—6,600-volt Three-phase Synchronous Motor Generator Set for South African Railways, 2,000 kW. at 3,000 volts.

50 cycles is generated at Colenso, and is stepped up for transmission purposes to 88,000 volts at the substations, and this is reduced to 6,600 volts and converted to 3,000 D.C. by synchronous motor generators.

Twelve substations have been installed, all for complete automatic operation, and the standard motor generator set has a capacity of 2,000 kW. Four stations are equipped with one machine, seven stations with two machines, and

one station with three machines. Each motor generator set consists of a 6,600 volt three-phase 50-cycle synchronous motor, direct coupled to two 1,500-volt generators designed for series operation, together with two exciters, one for the motor and one for the two generators. The five machines are mounted on one bedplate built in three sections, and the rotating element is supported on four pedestal bearings (see Fig. 58).

The rating of each set is 2,000 kW. at 3,000 volts, and the overall efficiency is 90 per cent.

Tests.—The specification states that the machine must be run continuously at full load until the temperature is steady, and immediately afterwards at 50 per cent. over-

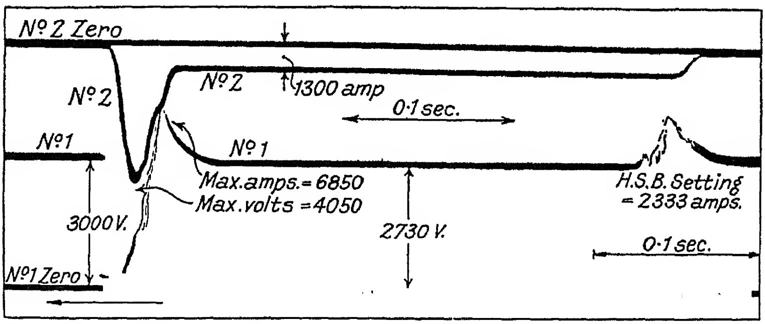


FIG. 59.—Oscillogram of Short Circuit on 2,000-kW. Motor Generator Sets for the South African Railways.

load for thirty minutes. It must also withstand three times full load, that is 6,000 kW. for five minutes, and a momentary overload of 7,000 kW., commutation to be practically sparkless through the whole range. In addition, the machine must be deliberately short-circuited several times without any sparking at the commutator or injury to the machine.

These motor generators, which were constructed by the British Thomson Houston Co., were subjected to all these very drastic tests before being sent out to South Africa, and withstood them successfully. The oscillogram shown in Fig. 59 illustrates the way in which the high-

speed circuit-breaker cuts out the machines, and also the extent to which the current rises on a short-circuit.

As this set has several unique features, a more detailed description of the method of working is given.

Starting. This is done by the reduced voltage transformer tap method, and when the speed has reached 475 r.p.m. (synchronous speed 500), the motor field is connected to the two slip rings from which it receives its supply, this being done automatically by a pivoted arm actuated by centrifugal force. As the field comes up, the motor is pulled into synchronism.

The direct-current generators have six poles, thus allowing for a large distance between brush-holders, and are provided with compound windings, commutating poles, and compensated pole face windings, to ensure sparkless operation on overloads. The series winding of each D.C. generator is in duplicate, one being cumulative to the shunt winding when running as a generator, and the other differential under the same conditions. This is to provide for parallel running under all conditions, including reversed operation during regeneration.

The exciter for the D.C. generators is a compound machine arranged to keep the volts constant at 110. The exciter for the synchronous motor is rated at 36 kW. 170 volts, and is provided with four distinct field windings, two series and two shunt. One series winding is cumulative, that is assists the main shunt winding, and the other is differential, that is opposes the main shunt winding.

Robust Machines Necessary. The conditions which govern the design of a traction substation are substantially different from those which are called for in a substation used for town lighting, and the machines have to be more robust, as the number and severity of the short-circuits which they have to stand is greater. On the other hand, fine regulation is not necessary, and generally what regulation is required is done by compounding.

The network on the D.C. side of a traction substation is very much simpler than in the case of the lighting

substation, and this, taken with the fact that the permissible variation of voltage is much greater, makes the traction substation very suitable for complete automatic control.

Automatic Control. Large traction systems are now being electrified from substations, the whole of which are automatically controlled; but as far as the author is aware, this has not been done in the case of lighting and power supply to a large town.

A very important point to remember, when considering the relative merits of manual and automatic stations, is that provision must be made for interest and depreciation on the extra cost of the automatic equipment, and that it generally does not pay to instal more than one or two units in an automatic station, because the extra cost of the automatic equipment increases with the number of equipments per station, whereas the cost of attendance does not.

Electrification of the Southern Railway. This forms an outstanding example of the advantages to be obtained by converting from steam to electric traction for suburban services. The large increase in the number of trains that is possible greatly diminishes the overcrowding that was so prevalent, and the increased acceleration reduces the time on a journey as much as ten minutes in forty minutes. Getting into and out of the termini is greatly simplified, as no shunting of engines is required, and the available platform space is more usefully occupied.

In June 1927 the number of track miles electrically equipped was as follows:

South Western Section . . .	245 miles.
Brighton Section	152 ,,
South Eastern Section . . .	250 ,,

and in March 1929 the total number of single track miles electrified, including sidings, in all sections, will be 745.

This is the largest scheme of suburban electrification which exists at present, and it is only a beginning. There is no doubt that eventually practically the whole of the lines of the Southern Railway will be electrified.

The South Eastern Section, which is the latest to be equipped, has twenty substations, all of them of the attended type; but on the South Western section a few of the unattended or automatic type have been installed.

For the twenty substations in the South Eastern Section current is taken at 11,000 volts from the Deptford station of the London Electric Supply Co., by means of seven 0·25 sq. inch three-phase, 11,000-volt, 25-period feeders, and these terminate in the principal substation at Lewisham. The power is distributed from this station to all the other substations at 11,000 volts, and the whole of the metering is done at Lewisham. The unit in all substations is the 1,500-kW. rotary converter. Lewisham has four of these, a few stations have three, and the rest two.

These rotary converters are six-phase, compound wound with transformers, stepping down from 11,000 volts, three-phase, 25 cycles, to 660 volts D.C. They are constructed by three English firms, and have to stand very severe overloads and short circuits.

Tests. The tests to which they are subjected are as follows: 25 per cent. overload for two hours, 150 per cent. overload for twenty seconds, 200 per cent. overload for ten seconds. No flashing over at commutator or destructive sparking. The machine must also stand a short-circuit made by dropping a heavy metal bar across from the live to running rail, a short distance from the substation, this test being repeated several times.

The switchgear is of the cubicle type, made up of special composition slabs built up with a steel framework. The current transformers for the balanced current protective gear and instruments are of the bar primary type, fitted with extra long porcelain insulators, and carrying shields for the secondary windings. The three-phase oil circuit-breakers have a separate steel tank for each phase. A high speed of break is obtained by means of powerful throw-off springs, and under short-circuit conditions the speed is accelerated by the magnetic forces produced. Breaking capacity is stated to be 180,000 kVA.

Mercury Arc Substations on the Midi Railway.

As already mentioned, the Midi Railway was originally designed for the single-phase system. The single-phase current at 60,000 volts, 16–2/3 cycles was distributed to the various substations along the line, where the pressure was stepped down to 12,000 and applied to the trolley wire.

The system worked very satisfactorily, but when after the war the French Government decided to standardize on 1,500-V. D.C., this single-phase system had to be scrapped. It was decided to equip five of the substations, which previously had only been used for static transformers, with mercury arc rectifiers.

The electrical equipment of the four substations at Pau, Lourdes, Tarbes and Montrejeau, are identical, each station containing :—

Three three-phase oil-immersed transformers, with natural cooling and short-circuit-proof winding supports, output 1,750 kVA., 60,000 to 1,425 volts, twelve-phase.

Six absorption choke coils, each 188 kVA. 150 cycles, with natural cooling.

Three absorption choke coils, each 188 kVA. 300 cycles, with natural cooling.

Six mercury arc rectifiers, output 600 kW. each.

Three vacuum pump sets.

Three circulation cooling equipments.

Switchgear for the 60,000-volt A.C. and for the 1,500-volt D.C.

The Lannemegan station is similarly equipped, but contains four transformers of 1,750 kVA., eight absorption choke coils for 150 cycles, four absorption choke coils for 300 cycles, eight mercury arc rectifiers, 600 kW. each.

Each transformer, with three absorption choke coils and two mercury arc rectifiers, with accessories form a set of 1,200 kW. The first four substations, therefore, have an output of 3,600 kW. and the fifth 4,800 kW.

In each station one set serves as a stand-by.

Twelve-Phase Transformer. A rather unique feature in these substations is that the transformer is arranged for

twelve-phase, and it supplies two rectifiers each with six anodes. The secondary winding is sub-divided into four three-phase systems (see Fig. 60), displaced from one another by 90 electrical degrees.

The four star points of these systems, after passing through absorption choke coils, form the negative pole of one complete set. This special arrangement of transformer winding is in order to keep the pressure drop, when the load comes on, within very small limits, and it is claimed that the drop between full load and quarter load

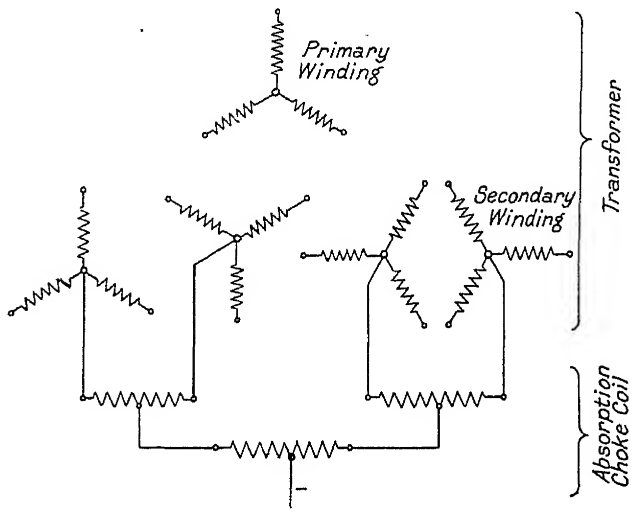


Fig. 60.—Arrangement of Transformer Windings to give twelve phases.

is only about 2·4 per cent. This is a very good figure, and is quite the right thing to do on a traction system; but it is only fair to point out that between quarter load and no load the pressure rises very rapidly, and at a very small load may increase to the extent of 25 per cent. It is clear, therefore, that the special winding would not be suitable in the case of transformers supplying town lighting through mercury arc rectifiers, as this rise of pressure would not be permissible.

These rectifiers operate in parallel with rotary converters

in other substations, and there seems to be no difficulty on this score.

Test Pressures. The following pressures were applied for one minute:

Between E.H.T. winding and L.T. winding, and between E.H.T. winding and earth	112,000 volts.
Between L.T. winding and earth .	3,500 ,,
Choke Coils, between winding and earth	3,000 ,,
Rectifiers, between casing and earth .	3,000 ,,

Cooling. The consumption of cooling water for the high vacuum pump, which is cooled with fresh water, is about 14 gallons per hour at 15° C. inlet temperature and 21 gallons per hour at 20° C.

Temperature. The temperature rise in the upper layer of the oil in the transformer by thermometer after $5\frac{1}{2}$ hours' run at 1,200 kW. was 25° C. and the temperature rise of the copper measured after the test by resistance was 25° C. E.H.T. winding, and 22·7° C. L.T. winding.

Efficiencies and Power Factor. The efficiency and power factor of this set are given in the following table:

	$\frac{1}{4}$.	$\frac{1}{2}$.	Full.	$1\frac{1}{4}$.
Power absorbed	350	692	1,325	1,670 kW.
Direct current	195	403	790	1,010 amp.
D.C. pressure	1,671	1,642	1,598	1,569 V.
Output	326	655	1,262	1,585 kW.
Power factor	·805	·905	·962	·965
Efficiency attained . .	93·2	94·7	95·3	95 per cent.
Efficiency guaranteed .	92·0	94·5	95·1	95 per cent.

Overloads. Fifty per cent. overload was applied to a rectifier set for three hours. At intervals of half an hour the load was increased to 200 per cent. overload for five to six minutes. The vacuum varied during the test

between 0·002 and 0·03 mm. Hg., and the temperature on the anode plate was about 35° C.

Short Circuits. To test how the rectifier sets would stand short-circuiting, a rectifier was set to work at full output on a water resistance with a short-circuiting device, or rather a very low resistance path, in parallel. In order to imitate conditions occurring in practice, ten short-circuits were made, one after the other, at intervals of one minute, the resistance over which the short-circuit was made being modified as follows:

0, 0·001, 0·006, 0·009 ohms.

For values exceeding 0·005 ohms, the primary switch did not trip, and the rectifier remained in service under its normal load. No damage was done to the rectifiers, and the railway company were satisfied with the test.

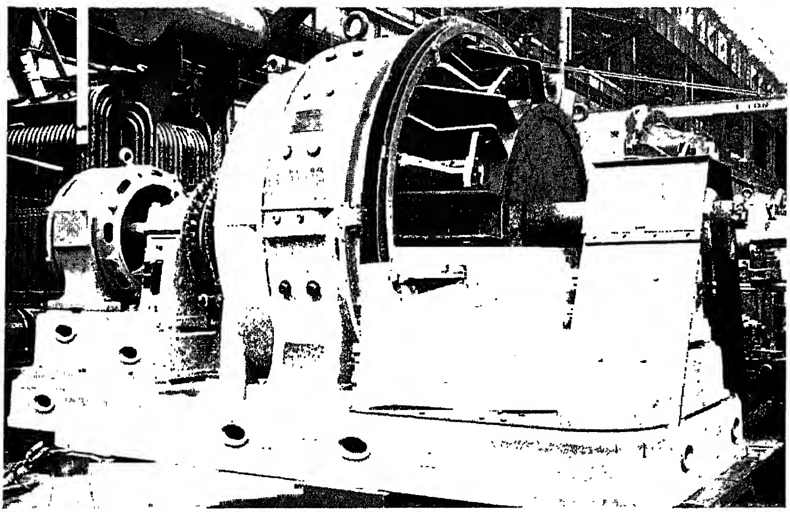


Fig. 61.—1,250-kW. Traction Type Rotary Converter, 750 volts.

Traction Type Rotary Converter. Fig. 61 illustrates a modern type of rotary converter for traction work, built by the Metropolitan-Vickers Co. and specially

designed to stand very heavy loads, and also short-circuits without flashing over at the brushes.

The voltage on the track is 1,500, and two of these machines, each giving 750 volts, are connected in series, and form one unit of 2,500 kW. The guaranteed overload capacity is $2\frac{1}{2}$ times full load for thirty seconds, ten times in succession, and $3\frac{1}{2}$ times full load momentarily. The machines also have to stand dead short-circuits without injury. These machines have been subjected to all these tests, and after twelve short-circuits had been made at two-minute intervals, there was no appreciable marking of the commutator.

Fig. 62 shows an oscillograph record of one of these

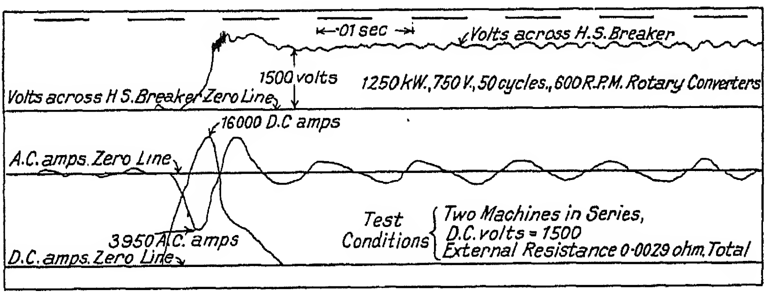


FIG. 62.—Oscillograph Record of Short Circuit on two 750-volt Rotary Converters running in series.

short-circuit tests, from which it will be seen that the D.C. current reaches a maximum of 16,800 amps., about ten times full load. This value is reached in ·009 seconds, by which time the high-speed circuit-breaker has opened sufficiently to cause the current to begin to decrease. The rate of fall of the D.C. current is very rapid in the early stages, but later on the rate of decrease is much lower, a very desirable feature, as it prevents any undue rise in the D.C. voltage, and in the case in point it will be seen that this D.C. voltage only rises to 14 per cent. above the normal.

Although the D.C. current rises to ten times the normal, it is interesting to note that the A.C. input only increases

to $3\frac{1}{2}$ times, this being due to the fact that a large proportion of the D.C. energy expended in the short-circuit is derived from the mechanical energy stored in the rotary converter armature. When a short-circuit occurs, the heavy current causes what may be termed an explosion at the brushes, and it is very necessary that the resulting copper vapour and carbon dust shall be removed as quickly as possible, to prevent a flash over.

This result is very satisfactorily attained by making the commutator with the same diameter as the armature, fitting a centrifugal fan between the armature and slip rings, together with a suitable enclosing cover over the fan, and a radial barrier between the D.C. brush gear and yoke coming to within a short distance of the commutator. This arrangement will cause a powerful draught of air to pass axially over the commutator face towards the bearing, and so dissipate rapidly any copper vapour, etc.

The large diameter commutator also has the advantage of giving a big distance between adjacent brush arms. It will also be noticed in Fig. 61 that arc deflectors are fitted on either side of the D.C. brush-holders. These are of simple and open design, and are arranged so that there is free room for the arc to be expelled axially, but at the same time it is prevented from travelling circumferentially round the commutator. In order to prevent the arc from reaching any grounded metal, the pedestal, shaft, and bedplate in the vicinity of the commutator are covered with insulating material. Also the front of the commutator is closed to prevent any tendency for the arc to be drawn inside the commutator.

CHAPTER X

NOISE AND ITS PREVENTION

There are two points of view from which this question should be considered: firstly, the effect of noise upon the substation attendants; and, secondly, the annoyance it may cause to neighbours.

Psychological Effect upon the Attendants. The ordinary substation attendant, when he takes up his duties, may find that the noise in the substation is troublesome to him, but he soon gets used to it, and if questioned after, say, six months, will probably reply that he does not notice it and it does not worry him. Without his knowing it, however, the noise has an effect upon him, fatiguing him and rendering him less capable. It is well known that some people who are particularly susceptible to noise, when starting on a long railway journey, will block up their ears with cotton wool, with the result that they arrive at their destination much less fatigued than they otherwise would have been.

Mr. R. M. Wilson, in his book *The Care of Human Machinery*, makes the following statement:

"Noise is no negative and negligible factor of life; it is positive and active, and can be ignored or discounted only by the expenditure of effort. In learning how 'not to hear' the noise energy is expended, and still more energy is expended from day to day in continuing not to hear it. The nervous system is bearing a burden which decreases the amount of its total value as an organizer of work."

Again, Mr. Hugo Munsterburgh, in his book on *Psychology and Industrial Efficiency*, states:

"The noise of machines, which in many factories makes it impossible

to communicate except by shouting, must be classed among the real psychological interferences, in spite of the fact that the labourers themselves usually feel convinced that they no longer notice it at all. Still more disturbing are strong and rhythmical sounds, such as heavy hammer blows which dominate the continuous noise, as they force on every individual consciousness, a psychological rhythm of reaction which may stand in strong contrast to that of a man's work. From the incessant struggle of the two rhythms, quick exhaustion becomes unavoidable."

Another point of very great importance is that the substation attendant depends very largely on his hearing for detecting anything wrong with the machines, and the greater the noise in the station the less likely he is to detect slight differences in sound, which are often the first indications of trouble.

Danger of Misunderstood Messages. Again, a noisy station makes it difficult for a switchboard attendant to communicate with his mate, and telephone messages are apt to be misunderstood. The telephone is essential for every substation, and the giving and receiving of messages and instructions are part of the routine duty. Serious trouble may be caused by a misunderstood telephone instruction, and it is very necessary that the possibility of this misunderstanding shall be reduced to a minimum. The author has found it necessary to instal. in some substations, telephone boxes having walls and door enclosing 3 inches of granulated cork: this has proved very effective.

The second point of view—namely, the annoyance to neighbours—is also of great importance, as it may involve the supplier in legal proceedings, and possibly financial compensation.

Chief Causes of Noise. The author feels safe in making the statement that the reader of this book has at some time in his life found that good brain-work, and particularly work which involves concentration, is impossible if a batch of robust children are playing close at hand. If he pauses to analyse why this particular kind of noise is so disturbing, he will find that it is mainly due

to the high-pitched note of the children's voices. Unfortunately it would appear that a large noise and a high pitched note are essential to the children's enjoyment, and if one suggests that they shall continue their game but with less noise, you will find that all the life has gone out of their play.

Other readers may have had occasion to be in the vicinity of a French locomotive when it lets off its soul-destroying shriek. In all these cases the trouble is due to the high-pitched note, and it is this that one must try to eliminate from the plant in the substation.

Mr. Alec B. Eason, in his book on *Prevention of Vibration and Noise*, classifies the noise made by electrical machines into three headings:

1. Magnetic noises, varying from a dull hum to high notes. They are objectionable and penetrating, and cannot easily be avoided in designing a machine. They are caused by high-frequency oscillations in the magnetic circuit.

2. Noises due to the load on the machine, caused by electrical or mechanical unbalance. These are of a low tone, and therefore not so disturbing.

3. Air noises: on the one hand of deep and unobjectionable tones due to the air set in motion by the fans, and driven out of the motor casing; and, on the other hand, of a high-pitched tone met with in squirrel-cage induction motors with high peripheral speed, and caused by the air being driven towards the field coils by the rotor.

The author is of the opinion that the air noises are the chief cause of trouble, and from his experience can state that the noises are not produced in squirrel-cage induction motors only, as he has found them very much in evidence in rotary converters. That these noises can be considerably reduced is certain, and recent experience with some 2,500-kW. motor converters, has confirmed this.

Some of the methods suggested by Pontecorvo (E.T.Z. 34, 547, 1913) are as follows:

Use symmetrical windings with an equal number of slots per pole and per phase. Use equalizing connections

and a large air gap. Chamfer pole tips and round all edges ; magnetic wedges should be used to close the open slots.

In unattended substations, where the effect of noise upon the substation attendants need not be considered, a method of neutralizing the noise of the machines is to build the substation so that it is sound proof. This has been done with some success in America, by arranging a building without windows, but with special arrangements for cooling by fans. The air is drawn through a lantern in the roof, and circulated through a duct in the floor into the machine and switch room, egress from this room being through a similar lantern and copper-gauze screen in the roof. A half-inch air space was left all round the foundation of the rotary converters. It is stated that the noise of the plant was inaudible about 6 yards from the building.

Enough has been said in the foregoing pages to justify the statement that noise is to be avoided, but paradoxically the other extreme, *i.e.* complete silence, is not in itself desirable. One cannot help being struck, when visiting a large static substation, or a mercury arc station, where an attendant is on duty, with the deadening and soporific effect of the absence of any noise, and one would imagine that the attendants at such a station would welcome a change. The obvious remedy is to do away with the job and make the station automatic, which should not be difficult.

CHAPTER XI

LIMITING RESISTANCES

Their Value in preventing Surges, and the Destructive Effects of Short-Circuit Currents. The increasing use of limiting resistances in connection with substations, both manual and automatic, is worth a little consideration, and why neutral point earthing resistances which in the past have been confined to generating stations will in the future be required in substations, also needs some explanation.

The Electricity Act of 1926 is now on the Statute Book, and its effect on the systems of supply is becoming clearer day by day. The tendency now is to eliminate the small uneconomical generating stations, to form the larger and more economical stations into groups, and further, to add, as required, super stations which distribute energy at very high voltages.

The existing large economical stations mentioned above are compelled to transform up from the voltages they have been working at (say 6,000 volts or 11,000 volts) to the voltage of the super stations, so that they can feed into the general supertension network. The substations of the existing companies have converting plant in them working at, say, 6,000 volts to 11,000 volts and it is therefore necessary for them to transform from the supertension pressure to the 6,000 or 11,000 volts.

These substations have probably in the past been working with an earthed neutral point, this earthing being done through a resistance situated at the generating station. The 6,000 or 11,000 volts at these substations now, however, comes from the secondary of the trans-

formers which reduce the pressure of the supertension mains, and therefore it is necessary to instal in these substations an earthing resistance which will pass sufficient current to work the protective devices on the cables and machines.

Earthing the Neutral Point through Resistance. The necessity for anchoring the neutral point of a three-phase system by connecting it to earth is now generally recognized. The two main advantages are: the prevention of surges, which commonly occur on systems where the neutral point is left floating, and the limiting of the current which flows to earth when a breakdown occurs.

With the present huge units of power that are being used all over the world, it is becoming increasingly necessary to avoid, wherever possible, a dead short-circuit, and present-day practice is tending towards the isolation of each of the three phases in a super-tension supply into separate buildings. Again, with regard to cables, the latest practice is to run three single-phase lead-covered cables, as in Paris, or to make up a cable of three single-core lead-covered cables held together by wire or tape armouring, as in the Henley S.L. type. The main object of the isolation of phases is to prevent the possibility of a dead short circuit between phases, as the currents which flow are enormous, and the possible explosive and destructive effects very great.

If, therefore, we make certain that any fault that may occur on the cables or in the switch house must be to earth only it is a tremendous advantage to insert a resistance in this circuit, and thus keep the current to such a figure that no destructive effect can occur. These earthing resistances have to be capable of passing very heavy currents for short periods, and the pressure across the terminals is that of one phase to the neutral point—in the case of the 11,000 volt system, this pressure is about 6,400 volts.

Carbon Powder Earthing Resistance. The author, about fifteen years ago, devised a carbon powder resistance, which has a large heat capacity, and is practically inde-

structible; it occupies a small space, and lends itself to alteration by merely regrouping the units. It further has the advantage of a negative temperature coefficient, which means that its ohmic value decreases as its temperature rises. If, therefore, due to a high resistance fault in the cable, sufficient current does not pass at once, the resistance heats up until the necessary current flows.

The Carbon Powder Earthing Resistance Unit (see Fig. 63) consists of a fireclay trough $23 \times 8 \times 2\frac{5}{8}$ inches, the recessed part being $21 \times 6 \times 1$ inches. The terminals

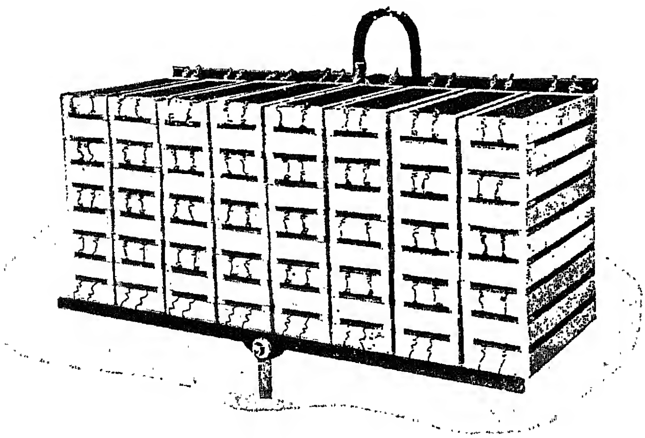


FIG. 63.—Resistance to carry 200 amperes on an 11,000-volt system installed at the Lancashire Power Company's Generating Station.

consist of L-shaped pieces of carbon which fit into slots moulded in the fireclay at the ends of the recessed part. Connection is made to these terminals by means of embedded flexible copper pigtails, exactly the same as is done in the case of the carbon brushes made by the Morgan Crucible Co. Two flexibles are fitted in each terminal, and to connect one trough to another the neighbouring flexibles are squeezed together between brass clamps.

This is by far the best method of making contact between copper flexibles and carbon, especially where high temperatures have to be dealt with, and the connection

between one trough and another is also very good, as one does not have to rely upon surface contact between two hard faces of metal, and the chance of any bad contact occurring is greatly reduced. One of these L-shaped carbon terminals is connected at each end of the trough, and carbon powder is filled in to a sufficient depth to at least cover the lower horizontal part of the L-shaped terminal. The standard voltage on each trough is 630, and the initial current 25 amps. A very large range in the ohmic value can be obtained, firstly by altering the size of the carbon particles which make up the powder, and secondly by varying the depth of the powder.

Earthing resistances are only called upon to absorb energy for a very short period, and the heat absorbing quality of these massive fireclay troughs is very valuable in this connection; as there is no need to allow for the cooling effect of air currents, the troughs can be packed quite close together, with asbestos packing pieces at the corners, and therefore occupy a very small space as shown in the illustration.

The troughs forming one pile are connected in series, the number being varied to suit the voltage on which they have to work, and all the piles are connected in parallel by a busbar running along the piles, one at the top and another at the bottom.

A great advantage of this type of resistance is that no iron structure or porcelain insulators are required, as the insulating properties of the fireclay are very good. The lead from the neutral point is brought on to the top bar and the bottom troughs, which are placed on the ground, are connected to another busbar which is solidly connected to earth.

The Carbon Slab Earthing Resistance. This is a modification of the carbon powder resistance, the carbon elements taking the form of plates $24\frac{3}{4} \times 13\frac{1}{4} \times \frac{5}{8}$ to $\frac{7}{8}$ inches thick. Three holes are moulded in each plate, into which fit the projections from porcelain insulators which rest upon the plate below. The resistance can therefore be built up into piles, as with the carbon powder

type, and it possesses the same advantage, in that no iron structure is necessary, and the lead which is at the highest potential above earth, is taken in at the top, the bottom plate being connected to earth. The resistance has a negative temperature coefficient, although the current, with constant volts on the terminals, increases at a much slower rate than is the case with the carbon powder type. This is an advantage, as the resistance can be left in circuit for longer periods without being damaged.

The following test, to which the carbon slab resistance has been subjected, illustrates its constancy under service conditions :

(1) Left on full voltage for thirty seconds with intervals for cooling ten times in succession. No change in ohmic resistance could be observed.

(2) Left on full voltage for $1\frac{1}{2}$ minutes with intervals for cooling ten times in succession. Resistance increased by only 12 per cent.

The last test is a very drastic one, as it is unlikely that under working conditions the full potential would be maintained across the terminals for anything like this time.

Fig. 64 illustrates one of these resistances, which together with the carbon powder resistance is manufactured by the Morgan Crucible Co. Other advantages are that they have a large thermal capacity, are non-inductive, the initial cost is low, and there are no maintenance charges ; they occupy a very small space, and there is no limit to the current or voltage for which they can be employed.

Cast-iron Grid Type Earthing Resistances. Cast grids of a special alloy form the units of which this resistance is made up. These grids are mounted on mica insulated rods, with mica washers for insulation between grids.

The sections of grids are arranged in tiers and assembled within a tubular framework, as shown in Fig. 65. The sections are connected in series or parallel to give the ohmic value and current rating required. The insulation between the sections of the resistance, and between the main frame and earth, has to be done by mounting them

on porcelain insulators, which may have to stand the maximum pressure.

A large number of grids have to be put in series, and the contact between one grid and its neighbour is made by the bosses cast on the grid. To ensure good contact these bosses have to be machined, and although, with

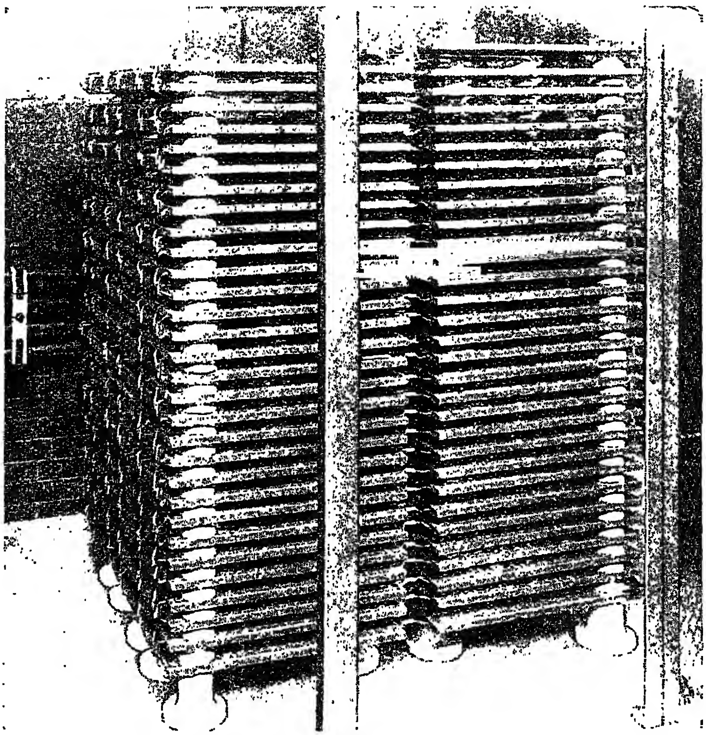


FIG. 64.—Resistance to carry 350 amperes on a 33,000-volt system installed at a large Power Company's Station.

care, a good job can be made, the contact cannot be so good as in the case of the carbon resistances, where connection is made by means of flexibles clamped together, at least two flexibles being used at each end of the plate or trough.

This resistance is different from the carbon type, in

that it has a positive temperature coefficient, that is to say, that as it heats up, the resistance increases. This is a disadvantage, as if the current passing at the time when a fault occurs is not quite sufficient to work the protective apparatus, the current can never reach the required figure, assuming, of course, that other conditions remain the same. In most cases, no provision is made for the earthing

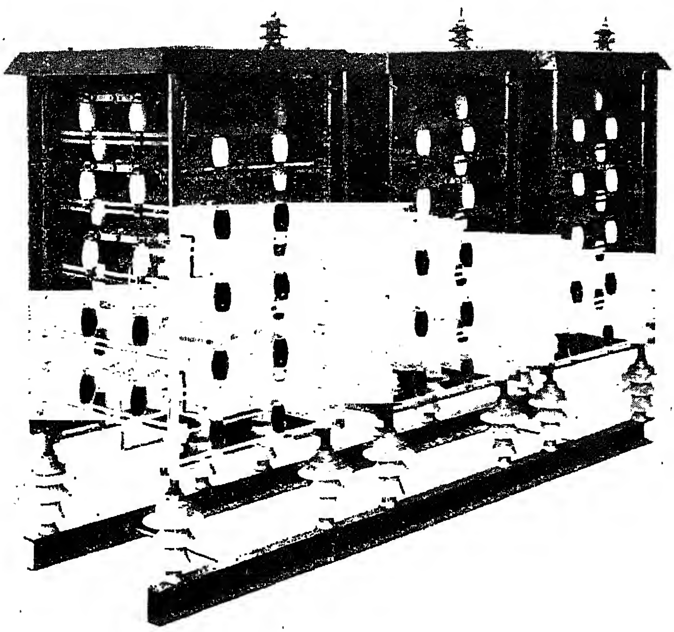


FIG. 65.—Cast-Iron Grid Type Earthing Resistance.

resistance, and it has to be placed in an odd corner, and in this case the grid resistance is at a disadvantage, as it occupies almost twice the space required for a plate type of carbon resistance.

Limiting Resistances on L.T. Feeders. Another case where limiting resistances are of great value, is in connection with the L.T. feeders from substations.

It has been, and probably still is, the practice in many

Supply Companies, when a short-circuit occurs on a feeder, causing the circuit-breaker to come out, to instruct the switchboard attendant to restore the supply by reclosing the circuit-breaker, three trials, if necessary, being made. Assuming that there is a dead short-circuit on the feeder area, the momentary current which passes when the

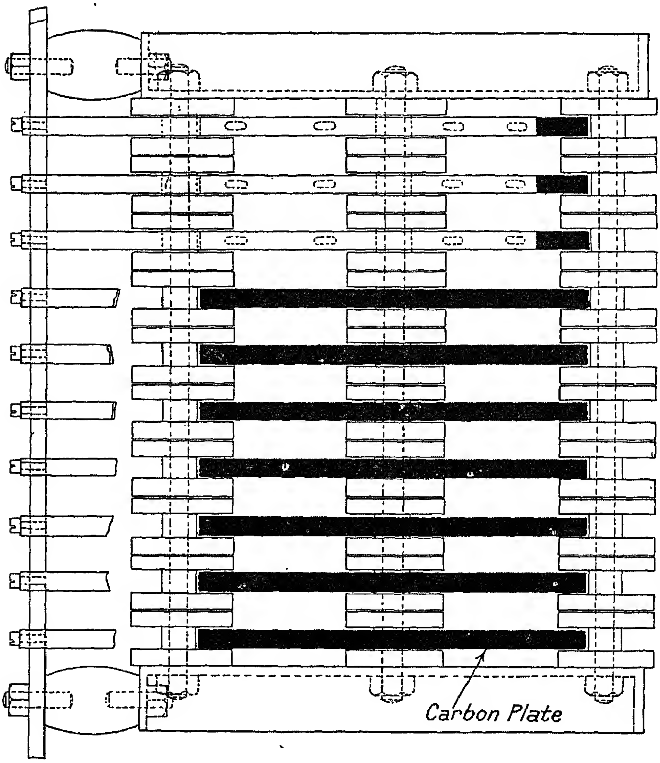


Fig. 66.—Plan of Carbon Plate Current Limiting Resistance for L.T. Feeders. Capacity, 1,000 amps., 9 volts.

breaker is closed is often enormous, with the result that severe surges are often produced, and breakdowns occur at other parts of the network. It is not generally appreciated to what high values these surges attain on a D.C. system. The late Mr. Duddell carried out some experiments on the District Railway, which showed that a rise

of pressure as high as 3,000 volts was obtained by the sudden interruption of heavy currents at 600 volts flowing a distance of some ten miles. (Paper on "The Electrical Equipment of Tracks on the Underground Railways of London," read before the Institute of Electrical Engineers in January, 1927.)

This practice of deliberately switching in on a short-

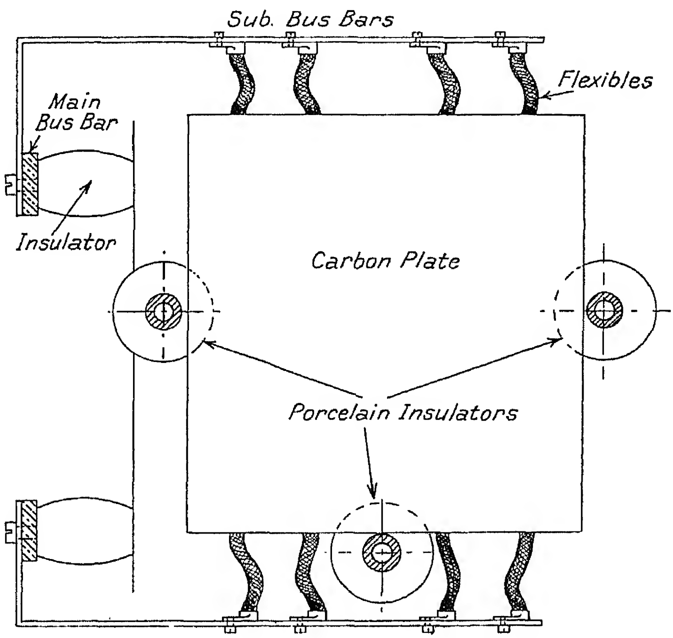


FIG. 67.—End View of Carbon Plate Current Limiting Resistance, showing Method of Connecting Plates to.

circuit is, in the opinion of the author, nothing short of barbarous, and should not be persisted in. The remedy is to switch the feeder in through a limiting resistance and to notice the current that flows. By this means it is comparatively easy to determine whether the short-circuit is still on, and if this is the case, the feeder must be left out.

Figs. 66 and 67 illustrate a new design of limiting resistance which has been in use by the author for some time past

with good results. It is used for limiting the current in very short low-tension feeders which, if left in parallel with the longer feeders without a resistance, would take too much current. It consists of a number of carbon plates similar to those used in the earthing resistance, arranged in a kind of rack in the same way as photographic negatives when they are being dried. Each plate rests on three porcelain insulators and has at each end four flexibles. These flexibles are attached to a subsidiary busbar, which in turn is connected to the main busbar. Each plate will carry continuously 100 amps. with 8 or 9 volts on the terminals, and as all the plates are connected in parallel regulation can easily be effected by disconnecting or connecting up the plates.

Limiting Resistances in Automatic Substations. The switching in of feeders on to a short-circuit, is done in the case of automatic substations in the same way as has just been described, except that the resistance is inserted automatically, and if the short-circuit is still on, the switch cutting out the resistance refuses to close.

These limiting resistances are also very largely used in connection with automatically started machines. If a machine is severely overloaded, or it has to be switched in with a short-circuit on the mains, a limiting resistance is inserted which reduces the current to a figure which will not damage the machine. Of course, the resistances cannot be made large enough to carry the current for more than a few minutes, but by that time the short-circuit, or the overload, may have gone off, and the resistance is then automatically cut out.

The resistance itself is protected by a thermostat, which is arranged immediately above it, and which switches off the circuit when the resistance attains a predetermined temperature.

Limiting Resistance to prevent Current Rushes when switching in Transformers. It has been noticed that when switching in a transformer on no load, the ammeter sometimes indicates an initial current (which immediately goes down), far in excess of the normal no

load current, and sometimes it is so great that it exceeds the normal full-load current, and causes the circuit-breaker protecting the transformer to come out. This is due to the fact that the initial value of the current in a transformer on no load at the instant of switching on is determined by the point of the pressure wave at which the switching in occurs, and also by the magnitude of polarity of the residual magnetism which may be left in the core after the previous switching out. This excessive rush of current may be prevented by providing the switches controlling the transformers with buffer resistances connected to auxiliary contacts, so that the resistances are connected in series with the transformer at the instant of switching in, and immediately afterwards cut out by the further movement of the switch. By inserting a resistance which only takes 5 per cent. of the normal supply voltage at no load, these current rushes can be reduced to a safe figure.

In the preceding pages some of the advantages to be obtained by the use of limiting resistances in electrical supply have been set out, and the author, who is a strong supporter of the modern tendency to isolate each phase in a three-phase supply, ventures to suggest that a great deal of the advantage of this isolation is lost, if the neutral point is connected solidly to earth.

With regard to the use of resistances on the L.T. side, while it is admitted that it is impossible to prevent short-circuits occurring on the mains, one must bear in mind the destructive effect of these short-circuits on the cable, and not repeat them by deliberately switching on to a short-circuit without any resistance in circuit.

CHAPTER XII

THE OUTDOOR SUBSTATION

In these days of large outputs and high voltages, the outdoor substation is becoming more and more important. Pressures of 220,000 volts, 110,000 volts and 66,000 volts are becoming quite usual, and the problem of transforming from these very high pressures to a lower pressure which can be utilized in a consumer's premises is one which requires a great deal of consideration.

The difficulty of designing a three-phase oil-immersed iron-cased circuit-breaker for dealing with these pressures is considerable, and at present 44,000 volts seems to be about the limit. Of course, it would be possible to design such a switch capable of dealing successfully with the currents at the higher pressures, but the size and cost of this switch would be very great, and it is generally recognized that for voltages of this order it is necessary to have single-phase totally enclosed switches, or each phase should be in a separate building. For very large powers, the oil break switch will still have to be employed in spite of the expense, but for smaller powers, and for isolating switches, of which quite a number are required, a cheaper form of construction is desirable. One is therefore thrown back upon the air-break switch, and as the space required for the arc to break circuit is often considerable, and contact with the walls of a building would be disastrous, the question naturally arises: Why have a building at all? If this is agreed, the whole matter is simplified very greatly, and the reduction in cost of the necessary switching apparatus is enormous.

The outdoor substation consists of a number of vertical

steel stanchions embedded in concrete, and connected horizontally by a number of cross-girders, which commonly take the form of a lattice girder. These lattice girders are connected together by other steel girders, and it is from these girders that the air-break switches, choking coils, and expulsion fuses are supported. The above brief description is enough to bring home to the reader that the outdoor substation is not a thing of beauty, and in fact it often is a serious disfigurement to the countryside. A building, although it may be quite plain, can be made to fit in with the surroundings, and it is a complete clothed structure, sometimes possessing a dignity of its own. Attempts have been made by choosing insulators of a suitable colour, and painting the steelwork so that it harmonizes with the surroundings, and thus avoid any startling contrasts, to render the outdoor substation less objectionable, and although this treatment has been partially successful, the outdoor substation, in the author's opinion, still remains an indecent unclothed skeleton.

Despite its ugliness, the outdoor substation has come to stay, as the economic value of low first cost is an overriding consideration, and if one was forced to enclose all apparatus inside a building, the detrimental effect upon the supply and distribution of electricity, which is now being undertaken on such a large scale, would be so serious that the æsthetic side would have to yield to the economic. The outdoor substation is of necessity restricted to the control of static transformers, and the feeders which come in and go out. It is clearly impossible to instal rotating plant converting to direct current, as it would be ruined by the rain and snow.

The majority of these stations would be of comparatively small capacity, say up to 5,000 kW., and the air-break switch should be quite capable of dealing with the load. The principle of the air-break switch is shown in Fig. 68. The contacts of the switch are mounted on porcelain insulators, and are provided with blades below to carry the current, and arcing horns above to rupture the circuit. These two contacts are joined together by a central

contact mounted on porcelain and capable of motion in a vertical direction. This contact is provided with two clips which make contact with the blades mentioned above, and also an arcing contact, which breaks circuit after the other contacts are separated. When the central contact arm is pulled down, an arc is started across the horns, and this ascends, with the result that the path of

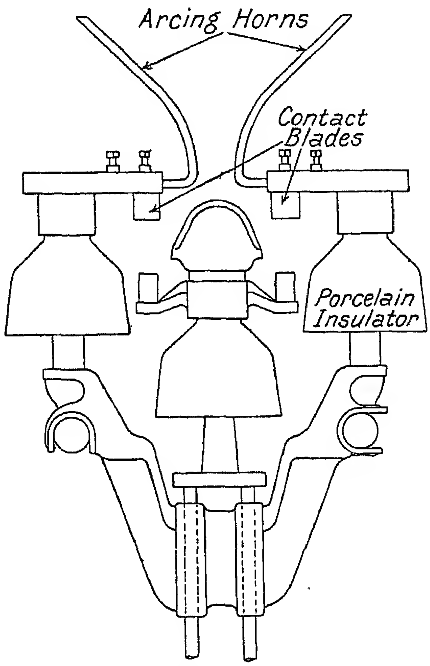


FIG. 68.—High-voltage Air-Break Switch.

the arc becomes larger and larger, until at last the arc is broken.

Apparatus made by the British Thomson-Houston Co. used in connection with outdoor substations is illustrated in Figs. 69, 70, 71. The first of these figures shows a three-phase isolator for voltages up to 44,000. This isolator is capable of breaking the arc due to transformer magnetizing currents, but of course is not suitable for

dealing with the heavier currents which flow when the station is loaded. It is used in connection with oil-immersed circuit-breakers as well as the air-break type, and serves to isolate any particular circuit switch or transformer, so that it can safely be worked upon.

By means of a key interlocking device, these isolators are interlocked with the main circuit-breaker, in such a way that it is impossible to break heavy currents on the isolators. The features of the interlock are:

1. The isolator can be locked in the open and closed

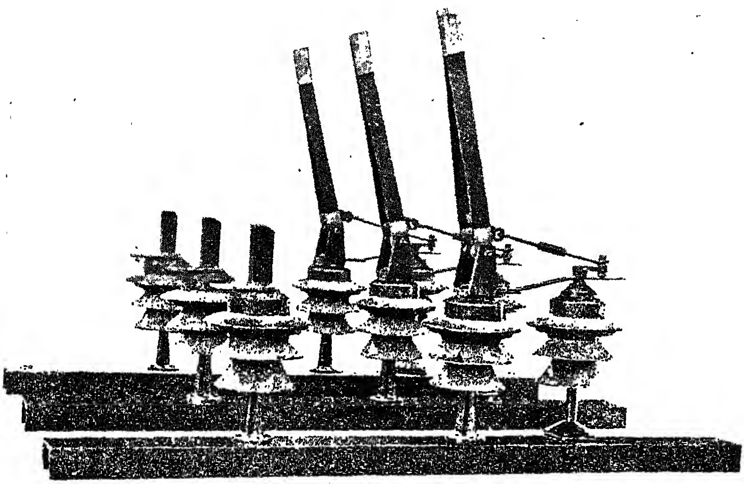


FIG. 69.—Three-phase Isolating Switch for a 44,000-volt Circuit.

positions. It is only when the isolator is locked in either of these two positions that the key is available.

2. With the isolator fully opened and locked, the key is available for unlocking the breaker control switch handle, permitting operation of the breaker for testing purposes.

3. The isolator cannot be operated while the breaker is closed, as the key is trapped in the breaker control switch, and can only be released after the breaker has been

opened, thus ensuring the correct operation of the isolator with regard to the breaker.

Fig. 70 illustrates a choking coil which is used to limit the rush of current on a short-circuit. It consists of bare hard-drawn copper rod, wound cylindrically, the turns being rigidly supported and braced at three points

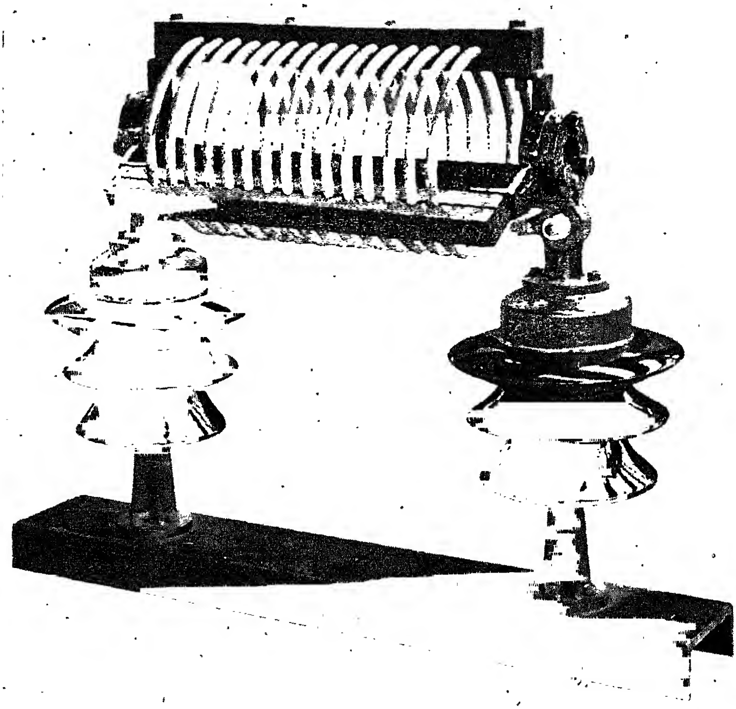


Fig. 70.—Choking Coil for a 44,000-volt Circuit.

around the circumference by specially treated wooden struts, which are securely bolted to metal spiders. The complete coil makes the construction capable of withstanding severe electro-magnetic stress.

Fig. 71 illustrates the expulsion cut-out, which serves to break connection when a short-circuit comes on the

system. The fuse carrier consists of an insulating tube enclosed in a porcelain housing. The ends of the tube are provided with cylindrical contacts which fit into spring contact clips mounted on pin type insulators. These clips exert a considerable pressure on the contacts, thus maintaining a good electrical contact. The contacts are protected against the effects of ice, sleet and snow, by means of a metal shield attached to the top of each supporting insulator.

When the fuse link melts, it forms a gas which expels

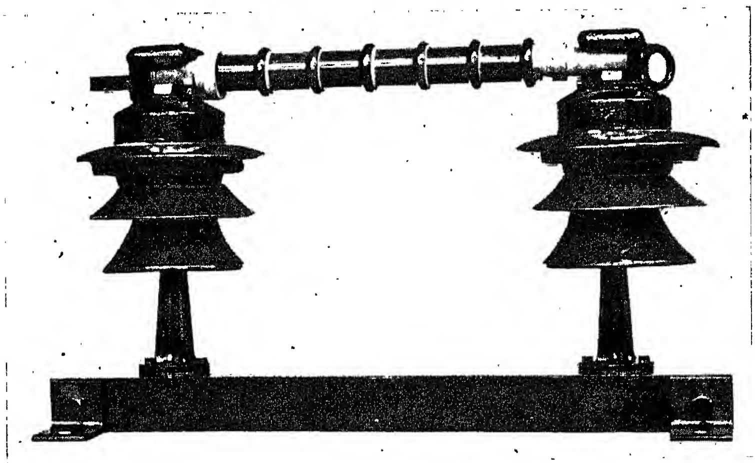


FIG. 71.—Expulsion Cut-out for 44,000-volt Circuit.

the arc at the open end of the fuse carrier, and therefore a clear space should be allowed at this end to prevent arcing to other apparatus or earth. The method of working these switches is by means of operating cranks and levers, which of course are thoroughly well insulated by means of porcelain insulators from the lever contacts. These levers can be operated immediately under the switch, or by a suitable mechanism at some more convenient distance. An up-to-date method is to erect a small building alongside the station, from which all the circuits, transformers, etc., can be controlled electrically

by remote control apparatus, but this of course is only done in the case of very large and important substations.

Fig. 72 shows a 3,000 kVA. 33,000 volt outdoor transformer substation, erected by the Metropolitan-Vickers Co., and Fig. 73 a very much larger station, 66,000/22,000

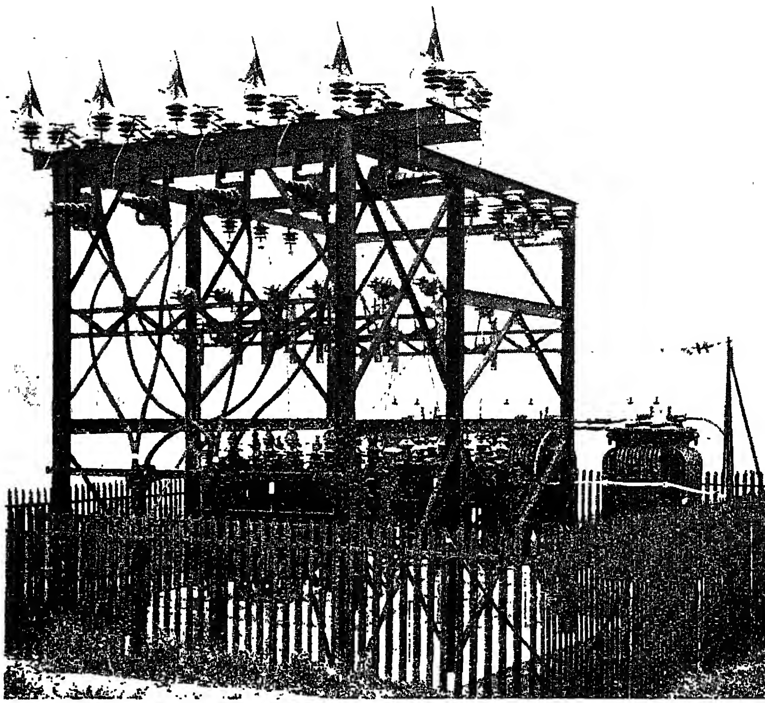


Fig. 72.—3,000 kVA., 33,000-volt Outdoor Substation at Betteshanger Colliery, East Kent.

volts with transformers, circuit-breakers and isolators, erected by Brown, Boveri & Co. These two illustrations show clearly that, provided sufficient ground is available, the outdoor substation is an exceedingly cheap and efficient way of dealing with switching problems at these very high voltages.

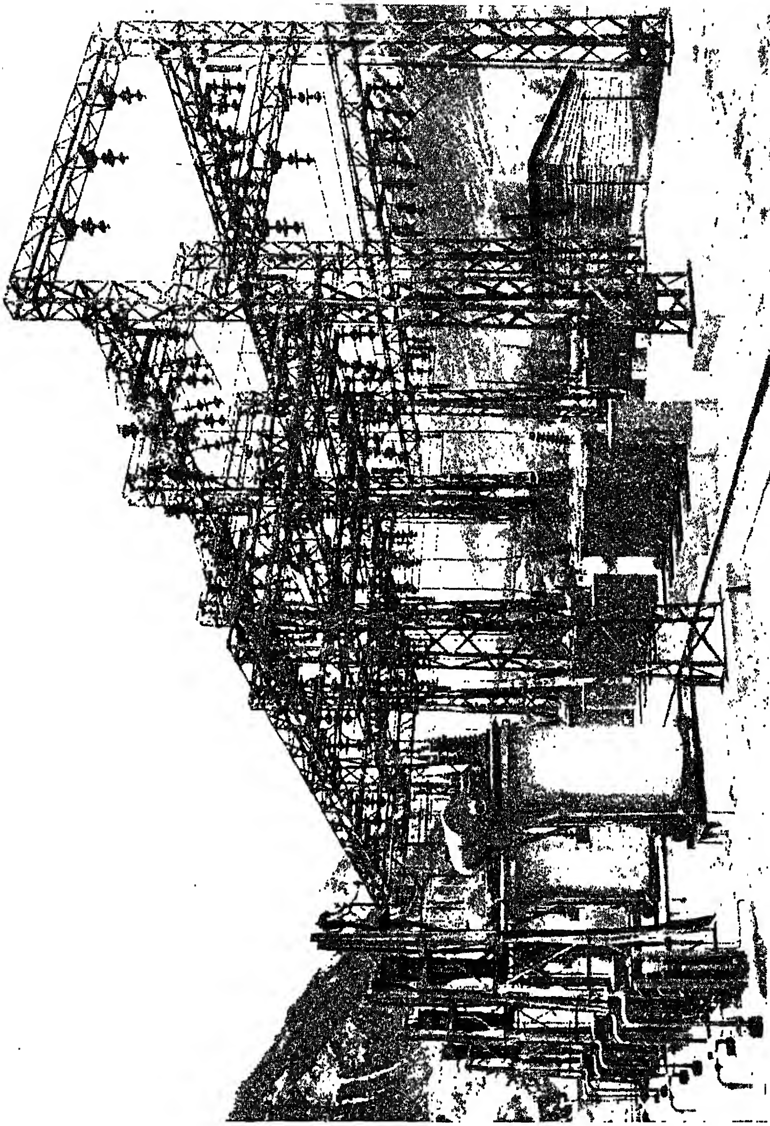


Fig. 73.—Outdoor Substation at Toutemagne, Switzerland, by Brown, Boveri & Co., consisting of three 8,400-kVA. Transformers, 10,000 to 63,000 volts, 50 periods single-pole oil circuit-breakers and isolator switches.

All that is necessary, when it is desired to erect one of these outdoor substations, is to specify the capacity, voltage, number and size of transformers, number of circuits and in which direction they enter the station, and the ground space available. The manufacturers can then set out the arrangement, prepare and drill all steelwork ready for erection, and the station can be erected in an incredibly short time at a very low cost.

CHAPTER XIII

AUTOMATIC SUBSTATIONS

In the author's opinion it is to the automatic substation that we must look for developments in the future. The subject is one of increasing importance, and now that sufficient experience has been gained to prove that they are thoroughly reliable a very large increase in the number of unattended substations is likely to follow. During the war, when the shortage of labour made the maintenance of electrical supply a difficult business, many engineers turned their thoughts towards the automatic substation as a way out of their difficulties. Development, however, during the war was not possible, and it was not till October, 1922, that the first fully automatic station was set to work in Great Britain, this being supplied to the City of Liverpool by the Metropolitan Vickers Co. It is of course true that quite a number of fully automatic substations were running in America before that date, and the credit for the initial development lies with the United States. The increase in America is prodigious, and as a conservative estimate we may say that there are working there about 700 automatic substations controlling about 800,000 kilowatts and also many thousands of automatic reclosing feeder installations.

It is not possible within the limits of the present book to describe fully all the different systems and apparatus involved, and, in fact, a whole book could be written on this branch of the subject. The author will endeavour, however, to discuss the chief points in connection with the selection of positions for automatic substations, the number required, size and type of plant installed, and the various

automatic systems that are in use at the present time.

When Automatic Stations are Justified. First of all it is necessary to come to a decision as to whether the installation of automatic substations is justified, and every case must be dealt with on its own merits. This decision is not an easy one to come to, as so many factors are involved; but one point stands out clearly, that those systems which are bound to continue supplying at a low voltage, say 100 volts two-wire or 100 volts three-wire (200 V. across outers), will require automatic substations first and will reap the most benefit from their use. The reason for this is fairly obvious, that beyond a certain point it is impossible to continue to supply from existing manual substations, as the cost of laying the extra mains to deal with the load becomes prohibitive and the pressure drop is so great that complaints are bound to arise.

It is a very extraordinary fact that such a go-ahead nation as America has standardized on a voltage of 115. This voltage was originally chosen because 115-volt lamps were more reliable and economical than 230-volt, but with the improvements that have been made in lamp manufacture this advantage has largely disappeared. On the other hand, the disadvantage of such a low voltage as 115 is now making itself felt more every day as the load increases so rapidly.

Converting plant for the voltage is much more expensive; it is less efficient; the expenditure in copper in the mains is enormous; and the range of supply is much more restricted. We can only assume that they are so deeply committed to this voltage by reason of the number of schemes using it that they cannot face any change. Probably also the standardization of lamps, fittings, motors, etc., for this voltage is so complete that the financial loss in making a change would be prohibitive. It is probably these facts which have led to the very much larger use of automatic substations in the United States.

If, however, we take a system, of which there are many in this country, which runs at 240-volt three-wire (480 across outers), and assuming the same current and the same

section of feeders in the two cases, we can convey 2·4 times the kW. for 2·4 times the distance for the same percentage drop of volts, or, to put it another way, we can carry for a given percentage drop of volts the same power $(2{\cdot}4)^2 = 5{\cdot}75$ times the distance. In the latter case, especially if there are plenty of spare ducts into which feeders can be pulled, the justification for automatic substations is not nearly so obvious, and it will pay to continue increasing the plant in the large manual stations for a very much longer period.

Increased Capacity of Mains Network. There will come a time, however, when this is no longer economical, and this time is brought nearer by another consideration, viz. the improvement in the capacity of the existing mains produced by installing an automatic substation say midway between two existing manual substations. If we take the lighting and power supply to a large town with manually operated substations containing a good deal of plant spaced as equally as possible over the whole area, it is obvious that feeders from these substations must vary considerably in length and there comes a time when the drop on the long feeders due to increased load is too great; if the busbar pressure is increased to compensate for this drop, the shorter feeders will be at too high a voltage. It is here where the automatic substation comes to our assistance.

By putting in such a station at the point where the pressure is low, one is enabled to take this load over from the manual station, thus allowing this station to lower its busbar pressure. By cutting the long feeders into two pieces and connecting up the far end into the automatic substation, we thus have two feeders made out of the one. If the feeder from the manual station is connected to the network at its new feeding point, it will carry a much larger current than previously without unduly increasing the pressure on the shorter feeders. We therefore see that the introduction of an automatic substation at a selected point enables the existing mains to be utilized to a much greater extent, and the saving in new mains will

go a good way towards paying for the automatic substation. The cost of mains laying in large towns is becoming greater every year, as the congested state of the streets renders it necessary to go much deeper than was formerly the case. Any scheme, therefore, which will do away with the necessity for new mains and will render the existing ones more effective is well worthy of consideration.

Selecting Positions for Automatic Substations. The best position for an automatic substation is fairly easily determined by an examination of the recording voltmeter charts which indicate the pressures at the various points in the system, and we now have to consider the number of stations to be installed and the capacity of each. Some engineers may be tempted by the fact that they can obtain a site for a large automatic substation at a given spot to instal a considerable number of machines in this one station, making it of a capacity which is comparable with the manual stations. This is a mistake from several points of view: *firstly*, the increased capacity of existing mains is not obtained in the same way as would be the case if the same amount of plant was distributed over two or three substations; *secondly*, the advantage claimed for automatic substations, viz. the saving in wages of attendants, is not obtained to the same extent as if two or three stations were put in. Moreover, the interest on the cost of the automatic gear required for a considerable number of machines in one substation may be greater than the saving by not having attendance in that one station. Some engineers take the line that automatic substations should not contain more than one set; but without agreeing to this statement the author is of the opinion that two sets, or at the most three, is the maximum number that should be allowed.

Capacity of Plant. And now as regards the capacity of the sets installed, it should be remembered that the cost of the main part of the automatic gear, the relays, etc., is the same for a small machine as for a large one, and that two machines each giving 500 kW. cost very much more than one machine giving 1,000 kW.

From the above it is clear that the thing to aim at is to put in the largest capacity machine that can be justified by the load which has to be dealt with. There is really no limit to the size of machine which can be started up automatically, and in the case of traction systems where the automatic principle is adopted throughout, sets of 3,000 and 4,500 kW. are employed with perfect success. In the case of automatic hydro-electric stations sets of 9,000 kW. are started up and switched in entirely without human agency.

Types of Converter. *The rotary converter* is the most usual type of machine employed, but *motor converters* are coming more into favour because the transformer with its possible fire danger is not needed and the space occupied is less.

In the case of traction systems working at 1,500 and 3,000 volts the double-ended motor generator and the mercury arc rectifier are installed, and both types lend themselves admirably to automatic operation.

For small capacity stations in outlying districts, particularly in residential neighbourhoods where the noise made by running machinery might be objected to, the *glass bulb rectifier* is utilized, and in this case automatic regulation of the voltage is possible by varying the tap connections on the transformers. In automatic stations controlling running machinery, whether rotary converter, motor converter or motor generator is used, the starting-up arrangements are very similar and a standard type of station with slight modification for the different types of plant can be evolved.

This is a considerable advantage, as an engineer can instal different types of plant throughout his system, according to the necessity of the situation, and yet use the same automatic apparatus, thus simplifying the work of the inspection engineers. This question of standardization of apparatus becomes of increasing importance as the system grows, and if all the apparatus in all the stations is the same the number of spares needed is much less. There are a considerable number of systems already

in existence for the automatic control of rotating converting plant both for partial and for full operation.

Although in some cases, owing to the existence of a considerable number of pilot wires between the manually operated and the automatic station, a number of operations can be started by merely pressing a push-button, it is now generally accepted that this partial control is not the best practice and that the whole of the process from the starting of the machine until it is connected to the D.C. busbars is far better left to automatic operation. This is termed a fully automatic substation. A system of supervisory control in connection with a fully automatic station is the most approved arrangement at the present time, as while it possesses all the advantages of automatic starting and regulating, etc., it enables a control to be exercised in the time of starting up and shutting down and also the switching in and out of D.C. feeders.

The author, therefore, proposes to deal mainly with the fully automatic systems, and will describe three types made by the Metropolitan Vickers Co., the British Thomson-Houston Co., and the Brown Boveri Co. (Mercury Arc Rectifiers).

The B.T.H. System of Automatic Control

The special features of this system are :

(1) The motor-operated master controller (illustrated in Fig. 74) which ensures the correct sequence of switching operations under all conditions. This consists of a cylindrical drum driven by a small A.C. commutator motor, the speed being reduced by means of worm-wheel gearing, so that one complete revolution of the drum occupies about fifty seconds. The drum carries a number of circumferential contact strips, which, as the drum rotates, make contact with fixed-contact fingers. These strips are interconnected in such a way that the various control circuits are only closed and opened in one definite sequence. This method of fixing the sequence is claimed to be superior to the ordinary electrical interlocks, as the

chances of failure are very small, and a good wiping contact is always assured.

(2) The auxiliary generator, which is driven from the rotary converter shaft, and which by means of an auxiliary field winding on the rotary converter, fixes the polarity, and prevents the necessity of reversing the field, if it comes up in the wrong direction.

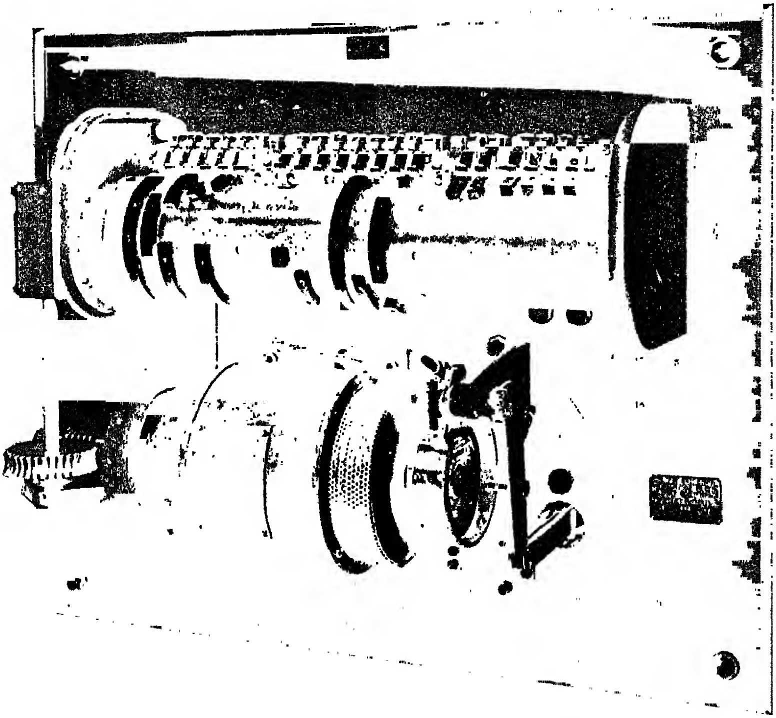
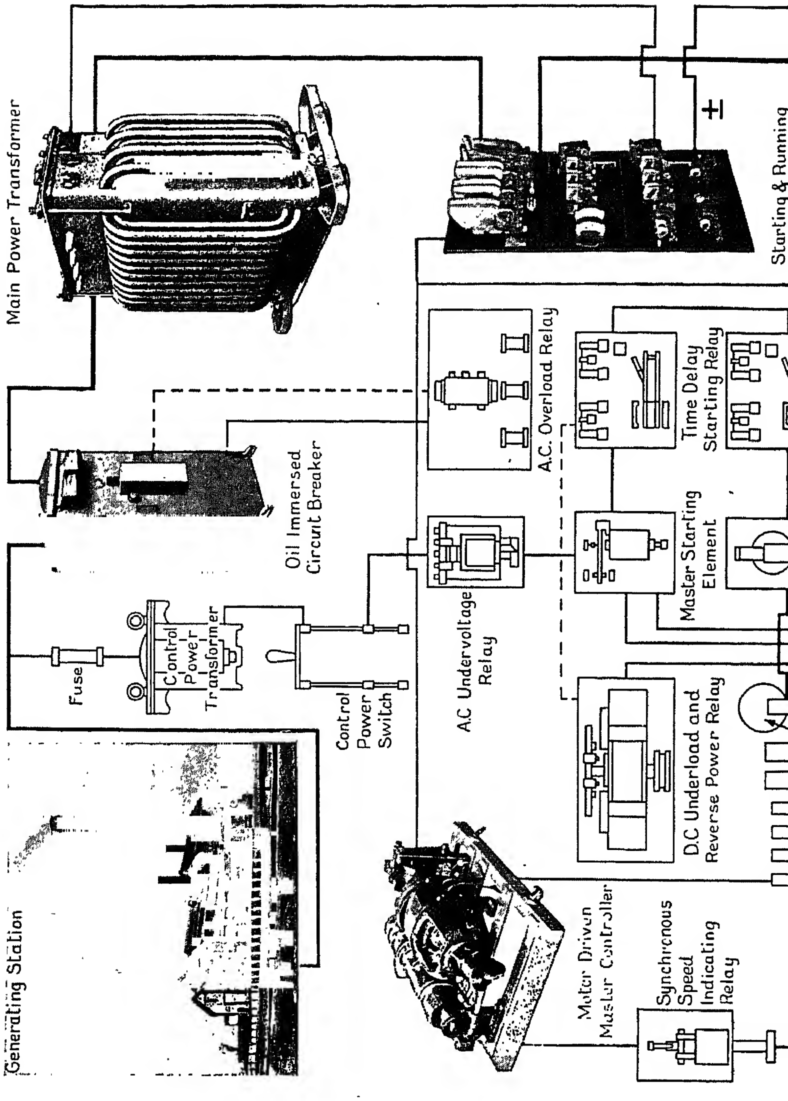


FIG. 74.—Motor-operated Master Controller.

(3) Induction motor for starting, which does away with the necessity for the brush raising gear required where the rotary is tap started.

Fig. 76 shows a one-wire elementary diagram of automatic switching equipment, for a rotary converter three-wire, shunt-wound, for ordinary power and lighting supply. Fig. 75 shows a graphic diagram of the equipment.


Main Power Transformer
Oil Immersed Circuit Breaker
Fuse
Control Power Transformer
Control Power Switch
Generating Station
A.C. Overload Relay
A.C Undervoltage Relay
Time Delay Starting Relay
Master Starting Element
D.C Underload and Reverse Power Relay
Motor Driven Master Controller
Synchronous Speed Indicating Relay
Starting & Running

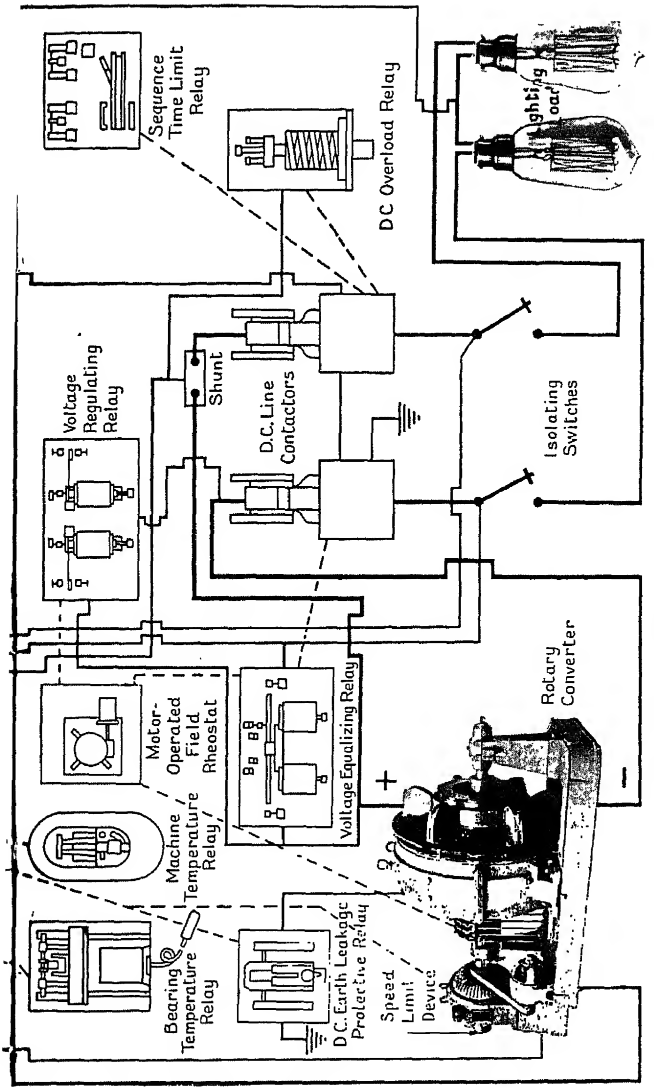


FIG. 75.—Graphic Diagram of Automatic Station Equipment.

The sequence of operations is as follows :

Starting. This can be initiated in several ways.

(1) When the load increases so that the D.C. pressure falls below a certain fixed figure, a master starting element

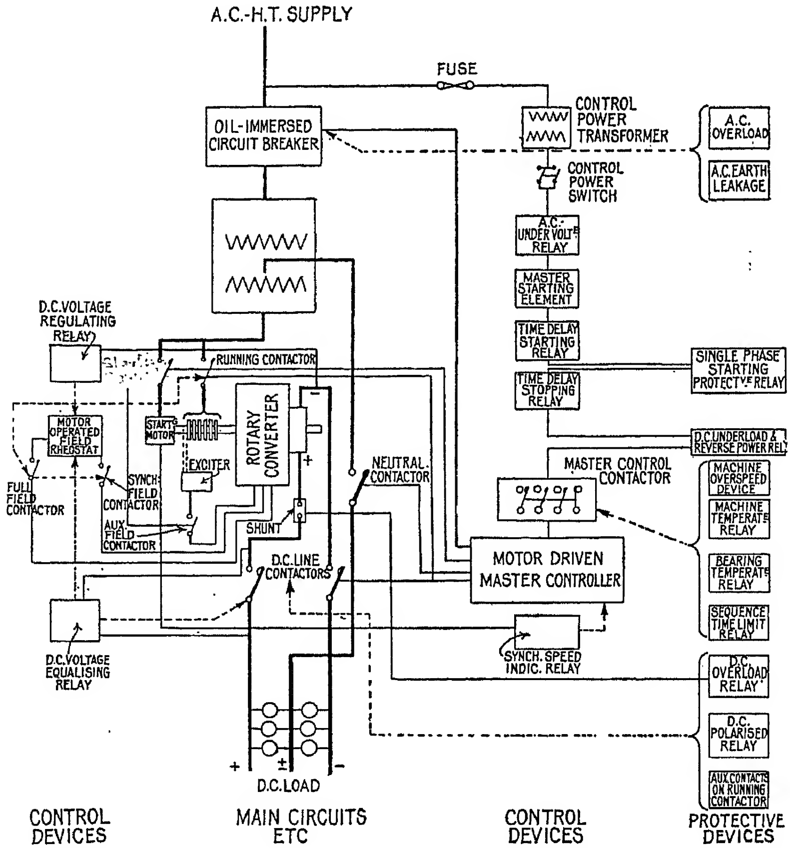


FIG. 76.—One-wire elementary diagram of Automatic Switching Equipment by the British Thomson-Houston Co.

comes into operation, and makes a contact which starts the automatic operation.

(2) By a manually-operated master control switch in some distant control room.

(3) By a time switch.

(4) By closing a high-tension feeder switch at the power station, or some other point.

Whichever method is used, the closing of the necessary contact energizes a master control contactor through a time-delay relay. The relay is included to prevent the equipment starting up due to momentary fluctuations of line voltage. The master control contactor is so interlocked, that it cannot close unless the motor-operated controller is in the "off" position.

The closing of the master control contactor causes the motor-operated controller to rotate, thereby closing the high-tension oil circuit-breaker; the main power transformer is now energized. Further rotation of the controller closes a "starting" contactor, and at the same time connects an auxiliary field winding on the rotary converter to an auxiliary generator which is driven from the rotary converter shaft. The starting contactor energizes the starting motor, and the machine starts. At this point the controller stops and waits for the machine to synchronize.

As the rotary converter accelerates, the auxiliary generator builds up its voltage, thus energizing the auxiliary field winding, and fixing the polarity of the machine. As the voltage of the auxiliary generator builds up, the motor driving the motor-operated main field rheostat, starts and rotates the rheostat arm to the "all in" position. When the voltage attains approximately 80 per cent. normal, the synchronizing field contactor closes, thereby adjusting the resistance in the main field of the converter to the correct value for synchronizing.

When synchronism is reached, a synchronous speed indicating relay operates and re-starts the master controller, thus closing a "running" contactor, and connecting the machine direct to the transformer, whilst the main field is disconnected from the synchronizing tapping on the field rheostat and connected to the moving arm of the rheostat. A "neutral" contactor also closes, thereby connecting the mid-point of the power transformer to the neutral of the D.C. system. This is followed by the

opening of the "starting" contactor. It will be noticed that the latter does not break circuit—it is only called upon to make circuit.

At the same time as the starting contactor opens, the auxiliary field winding is disconnected from the auxiliary generator. The controller now waits until the motor-driven rheostat has reached the "all resistance in" position, as mentioned above. When this operation is complete, the controller continues to rotate, thereby preparing the coil circuits of the line contactors for final closing. The controller ceases to rotate when it reaches the "running" position. Meanwhile, a voltage equalizing relay causes the field rheostat arm to rotate from the "all resistance in" position, until the voltage of the machine is equal to, or slightly greater than, that of the line, when the relay operates and closes an auxiliary contactor, which in turn permits the line contactors to close. When the machine is connected to the line, a voltage regulating relay controls the voltage.

The rotary converter continues to run, and supplies power until shut down by an underload, or by the operation of one of the protective devices.

Shutting Down. When the load on the machine falls to a predetermined value, an underload relay operates, thereby energizing a time-delay stopping relay. The time-delay feature incorporated in the latter relay prevents a shut-down due to a momentary fluctuation of load. When the period of time for which the relay is set has expired, the relay operates and interrupts the coil circuit of the master control contactor, thus causing the latter to open. This in turn causes the immediate disconnection of the machine from the D.C. busbars by interrupting the coil circuits of the line contactors.

A normally closed contact on the master control contactor, provides a circuit to ensure that the master controller is immediately rotated to the "off" position. As the controller rotates to the "off" position, it interrupts the coil circuit of the running contactor, thus disconnecting the machine from the power transformer; it also completes

the trip coil circuit of the high-tension oil circuit-breaker, which opens, thereby disconnecting the power transformer from the main transmission line. The master controller finally comes to rest in the "off" position, and the equipment is then ready to re-start when required.

Control and Protective Devices.

Overloads and Short Circuits. The rotary equipment is protected against overloads and short circuits by means of overload relays operating in conjunction with a controlling relay of the repeat action pattern, which can be set for any number of "notches" up to six.

When an overload or short-circuit occurs, one (or both) of the overload relays operates, and causes the line contactors to open: simultaneously the repeat action relay —which is provided with a timing device—advances one "notch." The switch arm of the motor-driven field rheostat is then rotated to the "all in" position; the voltage of the machine is then equalized with the line voltage, and the line contactors automatically re-close.

Should the line breakers remain closed for a period equal to the time setting of the repeat action relay, the notch is reclaimed. If, however, the fault persists, the line contactors are again opened by the action of the overload relay, and the cycle of operations is repeated. This cycle will continue until the repeat action relay has advanced to the last notch for which the relay is set, and will then finally operate its contacts, thereby shutting down the equipment until such time as the fault has been cleared and the relay re-set by hand.

Overspeed. Should the rotary converter attain an excessive speed, the equipment is shut down by an overspeed device, and locked out of commission until inspected.

A.C. Undervoltage. Should the A.C. voltage be too low, the equipment is prevented from starting by the A.C. undervoltage relay. Should the A.C. voltage fail during running, the machine is shut down by the operation of the same relay. The relay will re-set when normal voltage is restored, thus leaving the equipment free to go through

its sequence, and to reconnect the machine to the D.C. busbars.

Single-Phase Starting. The equipment is prevented from starting, unless all three phases of the high-tension supply are energized, by a single-phase starting protective relay.

Stalling. Should the automatic control gear fail to connect the machine to the D.C. busbars in a predetermined time, the converter is shut down and locked out, pending investigation by the operation of a sequence timing relay.

Overheating of Machine. A temperature relay, possessing the same heating and cooling characteristics as the machine, is provided, which shuts down the machine when, due to a sustained overload, the temperature of the machine has risen to a predetermined value. This relay will allow the machine to re-start when the latter has sufficiently cooled.

Failure of D.C. Supply for Control Circuits. Should the auxiliary generator fail to build up its voltage, the line contactors, which obtain their control current from this generator, would fail to close, thus the equipment would be shut down by the sequence timing relay. Should the auxiliary generator lose its voltage during running, the line contactors would open, thus disconnecting the machine from the D.C. busbars; after the time setting of the sequence timing relay has expired, the equipment would shut down.

Earth Leakage on D.C. Side. The D.C. earth protective relay shuts down the set should a flash to earth occur, or the insulation of the windings break down with an earth through the frame. This relay, being hand re-set, the equipment remains out of operation until the fault has been investigated.

Wrong Polarity. The inclusion of the auxiliary field winding separately excited from the auxiliary generator, ensures that the rotary will build up with correct polarity. The auxiliary generator is disconnected from the auxiliary field when the rotary is in service, to prevent any disturbance being transmitted to the auxiliary generator;

consequently the auxiliary generator always correctly excites the rotary when the latter is started up.

Hot Bearings. Bearing temperature relays shut down and lock out the machine, should any of the bearings become overheated.

Overheating of Starting Motor. Should the starting motor overheat due to too frequent starting, or failure of the rotary converter to synchronize properly, the plant is shut down and locked out of commission by the starting motor temperature relay, until the cause of the trouble is removed and the relay re-set by hand.

Reverse Power on D.C. Side. Any tendency of the rotary converter to run inverted, is prevented by the D.C. reverse power and underload relay. This relay being self-resetting, allows the converter to re-start when necessary.

Overload or Earth Leakage on A.C. Side. The high tension oil circuit-breaker is provided with time limit overload trip coils, and an earth leakage trip. Excessive A.C. overloads or earth leakage will trip this breaker, with the result that the machine is completely disconnected from both A.C. and D.C. sides. These trips are only intended to operate on very serious faults as being hand re-set they necessitate inspection before the equipment can again be put into commission.

The Metropolitan-Vickers Automatic Control System.

This method differs from the B.T.H. in that the system is self-contained, and does not employ a separate motor-operated controller, that no dependence is placed upon time lags only, or upon any mechanical sequence of operations, but that each operation depends on the proper completion of the preceding operation. No auxiliary generator is employed for exciting the field of the rotary and thus fixing its polarity, but wrong polarity is corrected in five seconds by a field reversing relay.

The tap-starting method is usually employed with rotaries, and this necessitates the provision of a brush-lifting device. Fig. 77 shows a diagram of connections

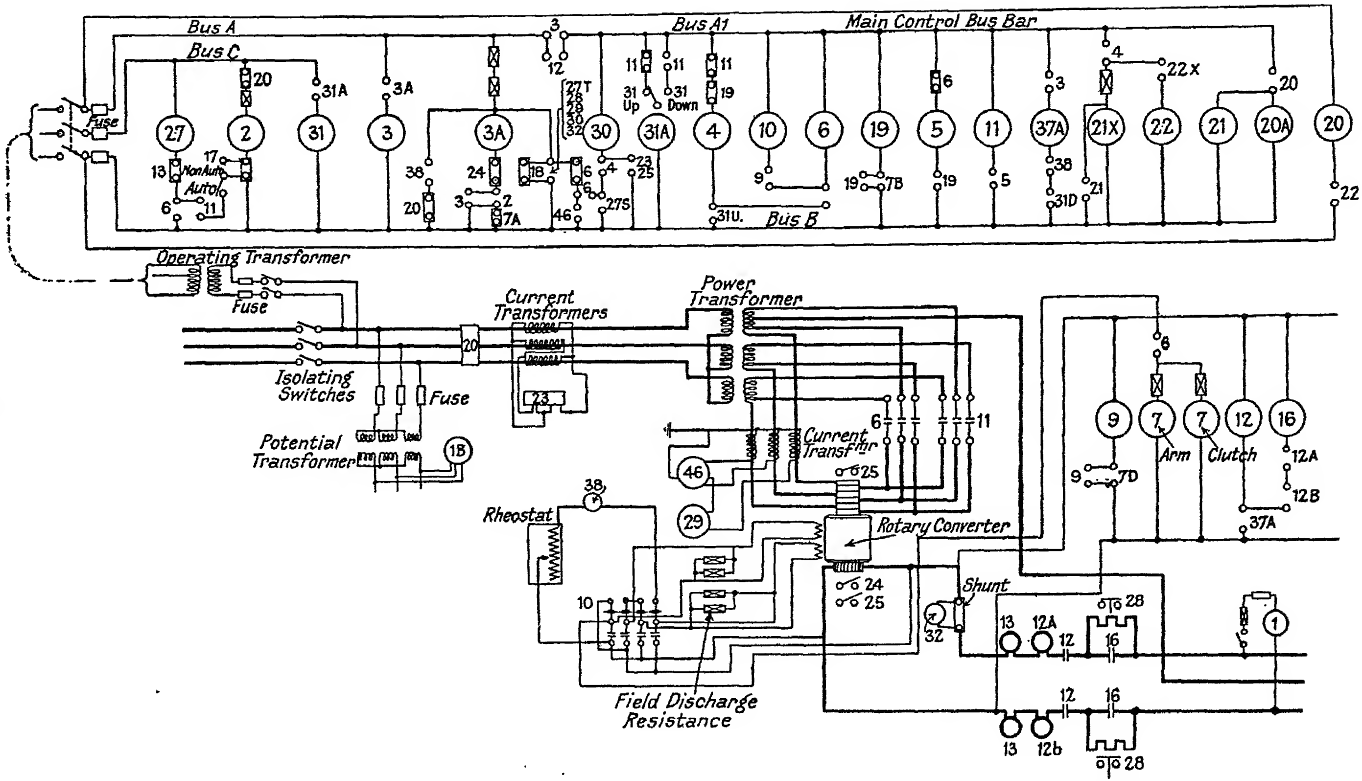


FIG. 77.—Diagram of Connections for a Metropolitan-Vickers Tap-Started Rotary Converter Automatic Equipment.

for a tap-started rotary, and also a key to the diagram. The starting up of the plant can be initiated in the same way as in the case of the B.T.H. system.

The complete sequence of starting takes from thirty-five to fifty-five seconds, depending upon the capacity of the plant, and on whether the rotary runs up with the correct polarity or not.

Operations in Starting. The actual operations in starting are briefly as follows :

1. On the occurrence of some predetermined condition, close the high tension oil switch and excite the step down transformer.
2. Close a contactor connecting the rotary on to the first low-tension transformer tap.
3. Check polarity on the D.C. side and if necessary reverse the shunt field connection to get correct polarity.
4. Close a contactor connecting the rotary on to the full voltage terminals of the transformer, after opening the contactor on the tap connections.
5. Connect the D.C. side of the rotary to the busbars through a load limiting resistance.
6. If the current drawn on the D.C. side is not excessive, short-circuit the resistance, and connect the rotary direct on the busbars.

KEY TO FIG. 77

1 Under Voltage D.C. Relay.
2 Induction Time Relay.
3 A.C. Shunt Relay.
3A ,, ,, ,,
4 ,, ,, ,,
5 ,, ,, ,,
6 A.C. Starting Contactor.
7 Polarized Motor Relay.
9 D.C. Rev. Field Relay.
10 4P. D.T. Field Contactor.
11 A.C. Running Contactor.
12 D.C. Line Contactor.
12a D.C. Accel. Relay.
12b ,, ,, ,,
13 Series Underload Relay.
16 Res. Shunting Contactor.
17 S.P. D.T. Knife Switch.
18 Rev. Ph. and Low Voltage A.C. Relay.
19 A.C. Shunt Relay.
20 Main Oil Switch.
20A Latch coil for Oil Switch
21 Induction Time Relay.
21X A.C. Shunt Relay.
22 Oil Switch Contactor.
23 A.C. Overload Relay.
24 Overspeed Device.
25 Bearing Thermostat.
27 Underload Delay Relay.
27T Delay Relay Time Contact.
27S Delay Relay Two Min. Contact.
28 Grid Thermostat.
29 Thermal Time Element Relay.
30 Lock Out Relay.
31 Brush Lifting Device.
31A A.C. Shunt Relay.
31U Brushes Up.
31D ,, Down.
31 Down Limit Switch.
31 Up ,, ,,
32 D.C. Reverse Current Relay.
37A A.C. Shunt Relay.
38 Field Current Relay.
46 Phase Balance Relay.

Operations in Stopping. The procedure in stopping is much simpler, the rotary being disconnected from both D.C. busbars and high-tension supply after expiration of the time lag in less than two seconds. The actual operations in stopping are as follows:

1. When load drops to a predetermined value, a time limit device comes into operation to ensure the plant does not close down merely to fluctuations in the load.
2. The control busbars are de-energized.
3. All D.C. and A.C. relays and contactors, and the main oil switch open, and the plant is entirely out of service.

Protective Features. An important feature of the apparatus is the inclusion of a complete range of automatic devices that give ample protection from possible troubles originating either inside or outside the substation. The arrangements are such that either the apparatus must function correctly, or automatically the protective devices either close down temporarily that portion affected, or permanently close down and lock out the whole equipment, depending upon the nature of the fault. In the latter case, the equipment remains shut down, until by the visit of an inspector the cause of failure to operate has been discovered and rectified.

Starting Sequence Protection. If for any reason the machine is not running correctly within two minutes of starting, the machine is locked out.

A.C. Overloads. On the A.C. side—overload relays are operated only by heavy overloads.

D.C. Overloads. On the D.C. side—overload or current limiting relays insert resistances in the machine circuits to restrict current to one and a half times full load current.

Rotary Heating Protection. A thermal relay having temperature characteristics similar to those of the machine protects against sustained or repeated overloads, but allows machine to re-start when sufficiently cool.

Bearing Heating Protection. A thermostat in each machine bearing shuts down and locks out the machine should a bearing reach a dangerous temperature.

Resistance Heating Protection. A thermostat is mounted above the load-limiting resistance. It will close down the machine should the resistance overheat, but allows the plant to function again as soon as the temperature becomes normal.

Phase Unbalancing. A phase balance relay guards against both broken lines on the H.T. supply, and faults on the A.C. low-tension apparatus.

Reverse-Phase and Single-Phase Running. Protection is afforded against both these faults.

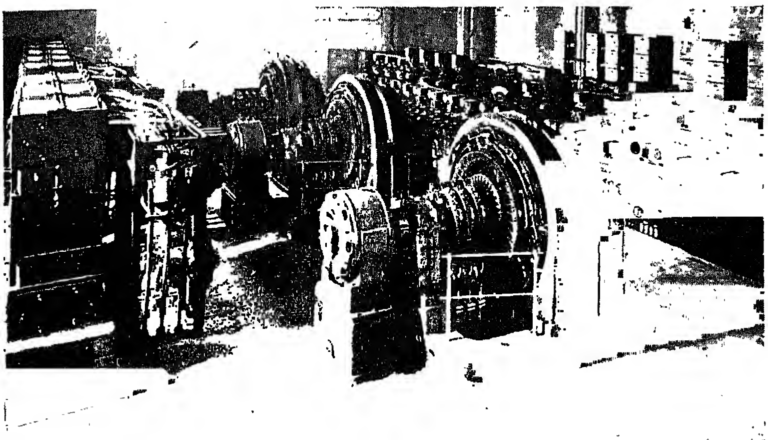


FIG. 78.—Three 1,500-kW. Automatic Rotary Converters at Balham Substation of City and South London Electric Railway.

Low A.C. Voltage. Protection is afforded both when starting up and when running against a low voltage.

No Field. If the field of the rotary fails, the machine is disconnected from the D.C. bars.

Overspeed. A speed limit device mounted on the rotary prevents excessive speed.

Reverse Current on D. C. Side. A reverse relay prevents reverse current operation.

Fig. 78 shows a typical automatic traction substation installed by the Metropolitan-Vickers Co. at Balham on the City and South London Railway.

The Mercury Arc Rectifier Automatic Substation

It must be admitted that the starting up of a mercury rectifier is a far simpler operation than the starting up of any other type of converting plant, and when we come to automatic operation, the simplicity of the apparatus required is still further emphasized. No running up to speed or synchronizing is necessary, no provision for reversing the field in order to correct the polarity, and the set is in commission in about ten seconds.

On the other hand, it should be pointed out that this simplicity is due to some extent to the fact that the mercury rectifier itself has no regulating properties, and if regulation is necessary, an induction regulator has to be inserted in the case of the high-power rectifiers and motor controlled tap changing in the case of the glass-bulb type. This involves additional switches, motors, and relays, and certainly makes the gear less simple. Even allowing for the regulation, however, the mercury arc rectifier automatic substation is very much simpler than the other types.

Fig. 79 is a simple one-line diagram showing the principal connections in an automatic station in Fribourg, used for driving the electric trams. No attempt is made to show how the relays are connected up, but the numbers of the relays and the arrows indicate the sequence of operation of these relays. The starting of the rectifier is initiated by a time switch, which energizes a relay, and thus causes the motor control to operate the E.H.T. switch. Auxiliary contacts mounted on this switch cause the ignition and excitation circuits of the rectifier to be closed, and the automatic valves for the circulating water to be opened.

As soon as the current in the excitation arc flows, it closes an interlocking relay, which brings the apparatus in connection with the closing of the D.C. switch into operation. First a relay closes, which tests to see whether the load is too heavy for the rectifier, or whether there is a short-circuit on. If either of these conditions exist, the D.C. switch will not close. If, however, the circuit is

normal, the D.C. switch closes and the rectifier is in service. If there is a short-circuit on the system, the automatic apparatus attempts at intervals of one-quarter, one, three and eight minutes, to close the circuit, and if the short-circuit still persists, the switch is locked out, and alarm signals are actuated.

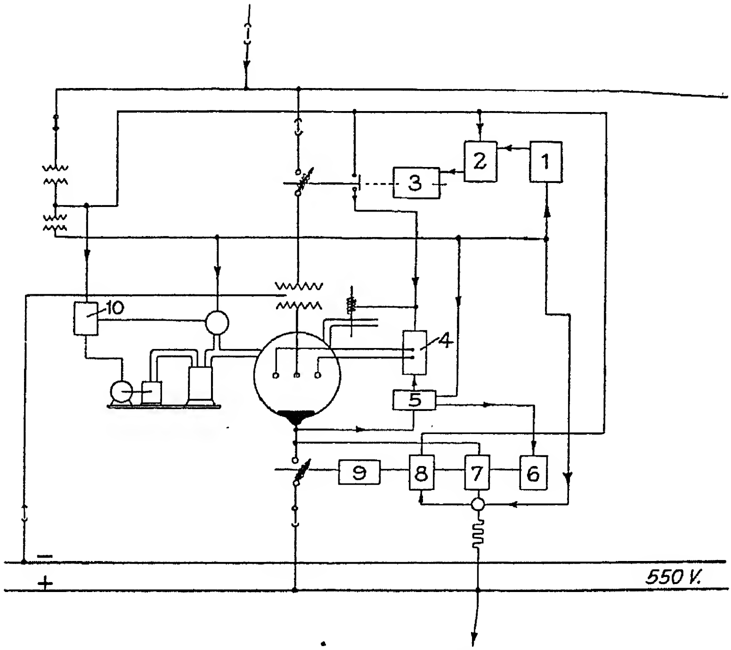


FIG. 79.—Diagram of Connections of Automatic Mercury Arc Rectifier Station at Fribourg.

When the short-circuit clears, a push-button, which may be controlled from a distant point, enables the interlock of the switch to be released, and the plant to be set in operation again. In the event of the rectifier attaining too high a temperature, owing to the flow of the circulating water being interrupted, a contact thermometer actuates a relay, and locks the rectifier out of circuit.

CHAPTER XIV

SUPERVISORY CONTROL SYSTEMS

To many engineers who have been working entirely with manually operated substations, it is somewhat of a shock to surrender all human control by installing substations, which start, stop, and regulate, entirely automatically, the control being provided by the variation of pressure on the L.T. mains. To such engineers, supervisory control systems, provided they can be guaranteed to be reliable, should be of great assistance.

The valuable features of automatic starting and regulating can still be retained, but superimposed on the automatic feature, a control can be exercised regulating the time of starting up and shutting down, and also feeder circuits radiating from the automatic substation can be opened or closed at will—a very valuable addition.

It is quite obvious that the simplest form of supervisory control system is one in which a pair (or one wire with a common return) of wires is installed for each operation it is desired to control. It is extremely unlikely that the number of wires required already exist between the control point and the substations, and the cost of laying these is generally quite prohibitive. This simple type of control may therefore be eliminated, and we are forced to consider other systems which employ but a few wires. These few necessary pilot wires probably exist between the automatic substation and the control point, and if a new substation is being put down, they would be laid with the ordinary trunk mains which provide the power to the substation.

There are several systems in use at the present time, but as they are somewhat complicated, it will be impossible to deal with all, and in fact the author considers that it is far better to devote his energies towards making one system clear to his readers, rather than attempt to describe several, with the result that none are understandable.

The system selected is that used by the Metropolitan-Vickers Co., and it is to them, and to the Automatic Telephone Manufacturing Co., that the author is indebted for the information which follows. He has endeavoured to make the principle upon which the system works understandable, but it is quite impossible with the space available to follow the whole of the operations right through. For example, to describe fully all the operations necessary to close one circuit-breaker would involve eight pages of this book.

An important point in connection with this supervisory system is that the apparatus used is exactly similar to the standard apparatus used in automatic telephone equipments, the reliability of which has been amply demonstrated by the successful operation of many equipments in all parts of the world. The most important part of the apparatus is the rotary stepper switch. Fig. 80 shows photographs of an actual switch, and Fig. 81 is a drawing of the working parts.

The rotary stepper switch as shown in Fig. 81 is known as a 4-level homing type. Each level, with the exception of the homing level, being provided with twenty-five contacts arranged in a semi-circular formation. The homing level, with which the homing wipers engage, consists of a continuous arc having one insulated first contact, which is coincident with the first contact position on the other levels. The purpose of this homing level is to maintain an electrical circuit during the period the stepper switch is rotating over the contact arc, and to release this circuit immediately the stepper switch returns to normal, *i.e.* when the homing wiper returns to the insulated first contact. All the levels are separated by

metal plates and insulators, the whole of the bank being finally clamped between two metal plates.

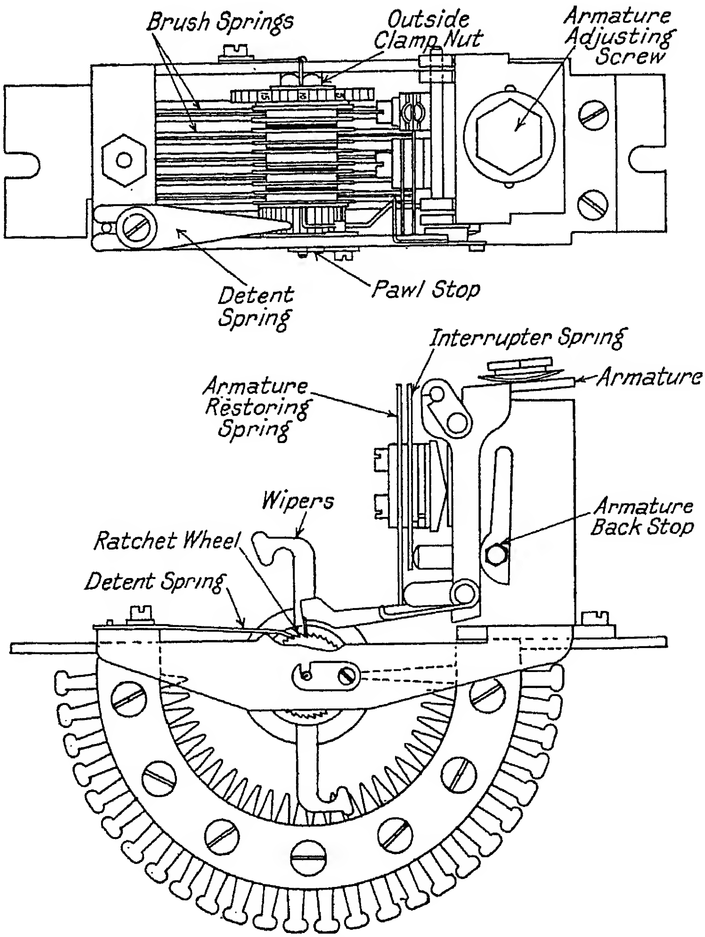


FIG. 80.—Rotary Stepper Switch for Supervisory Control System.

The Stepper Switch Wiper Assembly. This is built up of one, two, three or more double-ended spring brass contact wipers, each separated from one another by metal and insulating washers.

Ratchet Wheel. This wheel is so designed that the wipers continually rotate over the contact studs in a forward direction, connections to the wipers being made

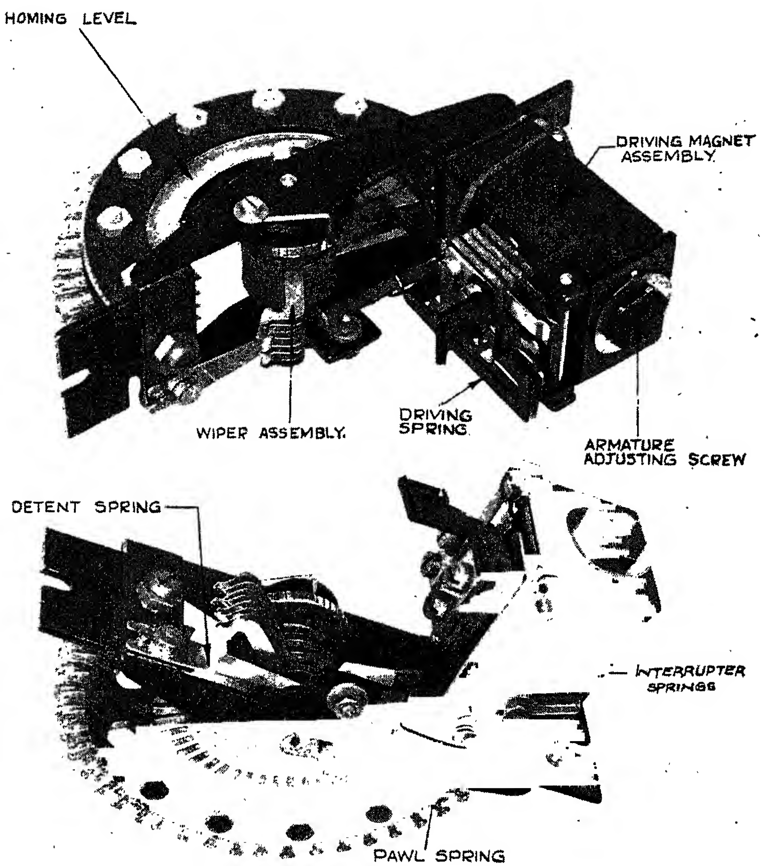


FIG. 81.—Rotary Stepper Switch.

by brush terminals, the fixed ends of which are secured to the bank.

The Driving Magnet Assembly. This comprises a heel piece and armature, the heel piece being so designed

that it encloses the magnet coil on two sides and one end, thus creating a closed magnetic path and therefore increasing its operating efficiency. At the extremity of the armature is pivoted the pawl, which engages with the teeth of the wiper assembly ratchet wheel.

It will now be appreciated that, when the driving magnet is energized, the armature forces the pawl over a tooth of the ratchet wheel, the extent of travel being regulated by the armature adjusting screw. The operation of the armature causes the pawl to ride over the crown of the next tooth of the ratchet wheel, and simultaneously the pawl spring completes the operation by forcing the pawl fully into the tooth notch. The pawl remains in this position until the electrical circuit of the magnet is broken, when the driving spring forces the armature and pawl back to the normal position, thus stepping the wipers on to the next set of contacts. A cylindrical stop mounted on the frame engages the pawl, and, in conjunction with the armature back stop, ensures that the wipers are correctly positioned in association with the bank contacts. A detent spring is fitted to eliminate back play during the forward movement of the pawl.

In addition to the various relays, the following equipment is required:

(1) **Control Room Equipment.** Two types are available.

Desk Type. In this type, an ordinary desk is provided, on top of which are mounted the necessary selector keys and indicating lamps. The various relays and stepper switches are usually mounted in the lower part of the desk, on hinged iron frames which can be swung out, thereby allowing easy access to the front and back of the relays and wiring. Removable dust-proof doors are fitted to the front and rear of the relay compartment.

In the case of a desk for controlling several substations, the relays, etc., would be mounted in small sheet-iron dust-proof cabinets separate from the desk.

Mimic Diagram Board Type. This consists of a vertical panel, on which there is painted a single-line diagram of

the main connections in the substations, with the selector keys, and red and green indicating lamps, mounted in positions corresponding to the various circuit-breakers (see Fig. 82).

This type of board is very convenient, as it enables the supervisor to visualize what is happening at the substations much easier than in the case of a desk having rows of keys.

The relays, etc., are mounted at the rear of the board in dust-proof sheet-steel compartments, and are easily accessible for inspection.

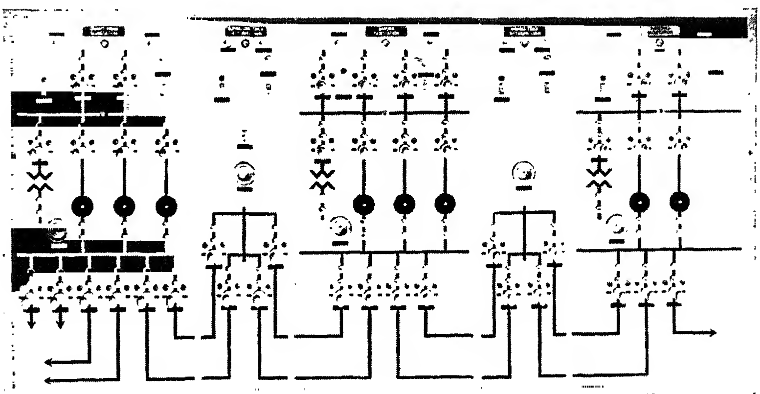


Fig. 82.—Mimic Diagram of Board Type of Control Room Equipment.

Details of Keys, etc. The control desk or board is provided with the following apparatus :

For each circuit-breaker controlled or indicated, there are—

1 2-way selector key (for closing or tripping).

1 red lamp for indicating when the corresponding breaker is closed.

1 Green lamp for indicating when the corresponding breaker is open.

1 White pilot lamp.

In addition to the above, the following items are provided :

1 Operation push-button.
1 Checking key, by means of which the supervisor may check the lamp indications at any time.
1 Yellow lamp which glows intermittently when selecting impulses are being sent out.
1 Red lamp which glows when any signal is received from the substation.
1 Alarm release key for extinguishing the above alarm lamp.
2 Blue lamps to indicate when a fuse blows on either the control room or substation equipments.
1 Testing jack, by means of which a special instrument may be connected to the pilot lines in order to test the condition of the latter at any time.
1 Alarm bell to give audible warning when any signal is received from the substation. This is stopped by means of the alarm release key mentioned above.

Each substation controlled has its own complete control room equipment, so that any one may be cut out of service at any time without affecting the operation of the others.

(2) **Substation Equipment.** The substation apparatus is mounted in a small sheet steel cabinet fitted with a dustproof cover (see Fig. 83). The relays and stepper switches are mounted on frames which may be easily removed for inspection.

The small telephone type relays do not directly control the circuit-breakers, as their contacts are not big enough to carry the various control circuit currents. Two interposing relays are provided for each breaker, one to close and one to trip, and the two relays are usually contained in one case mounted on the power panels. These relays are operated by the supervisory equipment, and in turn operate the circuit-breakers.

(3) **Pilot Lines.** Three pilot lines (usually 20 lb. telephone wires) are required per substation, but where a number of substations are controlled from one point, two wires are required to each substation, while the third

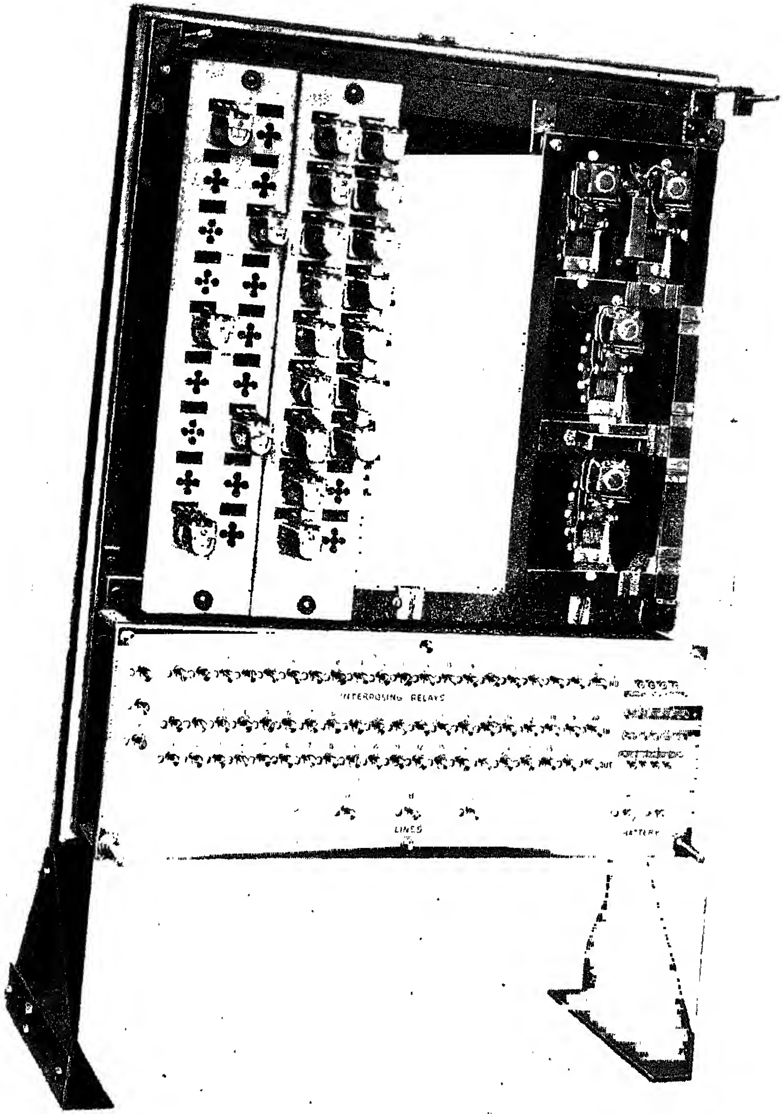


FIG. 83.—Supervisory Control Substation Equipment.

wire may be common to all. The number of pilot wires is not affected by the number of switches or other plant controlled in any substation.

(4) **Battery Supply.**

Control Station. A small 48-volt secondary battery of about 45 ampere hours capacity is required for operating the equipment. If desired, the various signal lamps may be operated from an A.C. supply through a small 12-volt transformer, in order to eliminate the continuous drain from the battery.

Substation. If there is an existing station battery, a tapping at 48 volts may be taken for operating the gear.

It should be noted that in the case of the substation equipments, there is no continuous drain from the battery, current only being taken during the few seconds that signals are being received or transmitted. For this reason, a small 48-volt primary battery may be provided, if there is no existing battery available. If preferred, however, a 30 A.H. 48-volt secondary battery may be used, arranged to be charged automatically by means of a small rectifier and time switch from an A.C. supply.

Sender and Receiver Apparatus. At the control room there are two groups of apparatus, the "sender" and the "receiver." The sender apparatus consists of the selection keys and associated relays for sending impulses to the substation to select the device it is desired to operate, and also the stepper switches. The receiver apparatus consists of similar relays, etc., which receive signals from the substation whenever a device therein changes its position. The incoming signals bring about the illumination of red and green indicating lamps, the red lamps going out and the green lamps lighting up, for example, when a circuit-breaker trips out.

Whenever signals are received in the control room, an alarm bell rings, and a red alarm lamp is illuminated to advise the operator, and, furthermore, when a circuit-breaker trips and its red lamp goes out and the green lamp

is illuminated, the latter continues flickering in and out until the operator releases the alarm bell circuit.

The apparatus at the substation end is similarly divided into two sections, one section, the receiver, being the apparatus to receive impulses from the control room as a result of which plant can be controlled, and the other portion, the sender, the function of which is to transmit signals back to the control room whenever a circuit-breaker or other device changes its position, the signals being initiated by auxiliary switches on the circuit-breakers themselves.

The current for the impulses referred to above is provided by the 48-volt battery already mentioned, and the method by which these impulses are initiated is of interest. This is done by means of two relays, the impulsing relay (307), and the stepper switch operating relay (304). When the selecting key is depressed, it energizes the stepper switch operating relay (304), which operates to energize the impulsing relay (307). This relay picks up and de-energizes relay (304), and the latter drops out after a short-time lag to de-energize (307). After a short-time lag (307) drops out, and (304) is energized again. These two relays make and break each other's circuit, causing impulses to be sent along the line until the stepper switch has moved through 25 contacts. Each time (304) picks up, the operating magnet of stepper switch is energized, causing the pawl to be advanced one tooth against a strong spring, and each time (304) is de-energized, the armature and pawl are forced back into their normal position, thus causing the stepper switch to advance through one contact. Each time a selector key is depressed, 25 impulses are sent from the control room to the substation.

The current impulses are all of the same polarity (positive), except one in each set of 25, which is negative. It is this negative impulse, which is brought about by one of the stepper switch wipers in the sender passing over a contact connected to the particular selector key which has been moved, which causes the impulse receiving relay

in the substation receiver to deflect in the opposite direction, whereby one stepper switch in the receiver at the substation is stopped at the particular contact corresponding to the operation it is desired to perform.

At the control room sender there are two stepper switches, F and G, and at the substation receiver there are three stepper switches, A, B and C. F at the sender and A at the receiver are not affected by the negative impulse referred to above, and step right on through the 25 contacts. G at the sender and B at the receiver are stopped when the negative impulse is sent. C at the receiver does not start until B stops, and it moves through the number of steps represented by the difference between 25 and the position of B.

For example, if it is desired to perform the operation corresponding to contact No. 5, which is reached after four impulses, B and G will stop at this contact and C will move as the result of 21 impulses, and when the impulses cease, it will be at rest on No. 22 contact (see Fig. 84). Now stepper switches B and C are interconnected, but in the opposite sense, that is to say—

No. 2 contact on B is connected to No. 25 on C.
No. 3 ,, ,, ,, ,, 24 on C.
No. 5 ,, ,, ,, ,, 22 on C.

So that in the example given above there would be a complete circuit through the two stepper switches, B and C, whereby a current is passed from the substation battery through the coils of two relays, one at the control room sender and the other at the substation receiver. These relays in turn prepare the operating circuit of the interposing relays selected, and when the operation button is depressed, this relay completes the local closing or tripping circuit of the circuit-breaker, which it is desired to control.

The object of this arrangement is to prevent anything happening through the faulty operation of the stepper switches. If, for example, stepper switch B failed to respond to one impulse, it would come to rest on contact 4,

but as there would be only 21 more impulses after it had stopped, C would still come to rest on contact 22. Now there is no connection between No. 4 on B and 22 on C, so that the circuit would be incomplete and nothing could be operated. Thus stepper switch C acts as a safeguard to ensure the proper functioning of the apparatus.

To close or trip a circuit-breaker, two distinct operations must be carried out.

(1) **Close the Selector Key.** This causes the apparatus

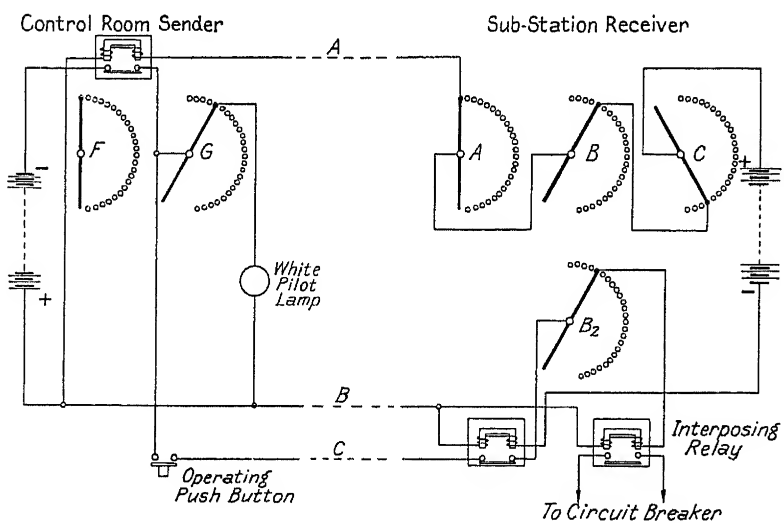


FIG. 84.—Supervising Control. Diagram showing Operations necessary for the closing of one Circuit-Breaker.

to complete one cycle of operations, during which 25 impulses (24 positive and 1 negative) are transmitted to the substations, causing the selection of the correct circuit-breaker. A white pilot lamp, individual to the selector key, glows, to indicate when this has been carried out. This operation is completed in approximately five seconds.

(2) **Close the Control Push-Button.** This, through the circuit prepared by the previous operation, causes the particular circuit-breaker selected to be opened or

closed. The selection as to the opening or closing of the breakers is made by sending a current in one direction for the opening, and reversing this current for the closing.

It is interesting to note that, in this system, two distinct operations are required before the circuit-breaker is operated, whereas with other systems the closing of one selector key is all that is necessary. In the latter case, the operator having once made his selection and operated a key, the operation is carried through to completion; and if he has made a mistake and selected the wrong operation, he cannot alter it or prevent it from being completed. In the Metropolitan-Vickers system, however, the lighting up of the white pilot lamp will call the operator's attention particularly to the key he has moved, and if he has made a mistake, or something has happened in the meantime to render that particular operation unnecessary or undesirable, he can cancel the selection and make another.

Again, in cases where plant is to be synchronized by supervisory control, as, for instance, with unattended hydroelectric generating stations, it is essential that the incoming machine oil circuit-breaker is selected ready for its instantaneous closure when synchronism is reached. This is only possible with the Metropolitan-Vickers system. The power of selection before operation is a very valuable feature, and this method is superseding the other.

It is impossible in this work to give a complete diagram of connections of all the apparatus necessary for the operation of a circuit-breaker, but the simple diagram in Fig. 84 may assist the reader to understand the method employed.

No attempt is made to connect up the various apparatus, but the diagram shows the position of the stepper switches when operation 5 has been selected, and also the interconnection of switches B and C.

Transmission and Reception of Signals, showing the Change in Position of Circuit-Breaker. Each circuit-breaker is fitted with two auxiliary switches, one of which is made when the circuit-breaker is in the " open "

position, and the other when in the closed position. By means of these auxiliary switches, whenever a circuit-breaker is closed or tripped, a relay is momentarily energized, which causes a stepper switch to operate and transmit signals along pilot wires back to the receiver in the control room. One of the wipers on the stepper switch passes over contacts, which are connected in such a way that, as the wiper passes over them, circuits are made, so that the signal currents are positive or negative according to whether the corresponding circuit-breakers are in the closed or open position.

These polarized signals are picked up by a suitable relay in the control room receiver, as a result of which the corresponding red lamp is illuminated, and the green lamp goes out when the associated circuit-breaker is closed, or the red lamp goes out and the green lamp is illuminated when the corresponding circuit-breaker is tripped.

The following contingencies are provided for:

1. If, when *signals* are being sent due to one circuit-breaker changing its position, another circuit-breaker also changes its position, the signal showing this change is transmitted immediately on the completion of the signals already being sent.

2. If selection *impulses* are being sent from the control room when a breaker changes its position, the selection impulses are cancelled out, the apparatus returned to normal position, and the *signals* are transmitted back to the control room, showing the change that has occurred in the circuit breaker position.

3. If several selection keys are operated simultaneously, only one circuit-breaker can be selected, and that will be the one associated with the contact on the stepper switch which is first passed over by the wiper during its movement of 25 steps.

4. The operator can check the position of the lamp indications whenever he so desires, by means of a key provided for that purpose.

5. In the event of a breaker being closed on to a fault,

and therefore immediately opening signals will be sent to the control room to indicate that the breaker has first closed and then tripped out again.

6. If for any reason during the transmission of *signals* the stepper switches in the receiver should get out of step with the corresponding switch in the sender, the signal would automatically be transmitted again.

7. Fuses are provided at both the control room and substation between the operating batteries and supervisory apparatus, and should any of these blow, a blue alarm lamp is illuminated and a fuse alarm bell rings.

CHAPTER XV

BRUSHES AND BRUSH-HOLDERS, HIGH-SPEED CIRCUIT-BREAKERS, END PLAY AND SPEED LIMIT DEVICES

The question of commutation is such a vital one in connection with converting sets in substations, that a little consideration of the best types of brushes and brush-holders is necessary. The practically universal practice at the present time is to use carbon brushes.

Brush Holders. Twenty-five years ago, when the output of machines was small, and the peripheral speed of the commutators was low, carbon brushes were tightly clamped on to aluminium or brass holders, which moved about a fixed brush arm.

The contact between the brush and holder was not always satisfactory, and the brushes had to be electrolytically coated with copper to improve this contact. In addition, flexible copper strips connecting the movable brush-holders to the fixed brush arm had to be provided. Even at these low outputs and speeds, a good deal of trouble was experienced in getting the current away from the machine. With the increase of output and peripheral speed due to modern requirements, this type of brush-holder becomes impossible, as its inertia is too great to follow up slight irregularities in the commutator, and bad sparking results. Also the current cannot be conveyed away without danger of excessive heating at the contact surfaces.

Brushes of the slide type are now almost universal. With this type, brush-holders accurately machined to fit

the brush must be employed. The brush-holders should be cast in one piece and adjustment should be provided to enable them to be set within $\frac{1}{8}$ or $\frac{3}{16}$-inch of the commutator, so that very little of the carbon brush projects. These points are very important, and the author has had bitter experience with brush-holders built up with brass strip, and standing about $\frac{3}{8}$-inch from the commutator. These had to be scrapped and replaced with the cast type, with very beneficial results.

Another very important point is that the brush must be readily accessible for cleaning and adjustment, as if dirt is allowed to accumulate in the box the brush will stick, and bad commutation results.

With the high peripheral speeds now in use, it is very necessary to reduce the inertia of the moving brushes to the minimum. This is best attained by using two brushes of half the thickness, and placing one of these behind the other in the brush box, a small plate of brass separating the two. With a machine giving 9,000 amps. a brush of $\frac{1}{2}$-inch thickness can then be employed. A brush gear of this type is fitted by the British Thomson-Houston Company on their motor converters. The brush gear is supported from the magnet yoke, and being of the radial type, maximum spacing is secured between adjacent parts of opposite polarity. Each individual brush can therefore be readily inspected, adjusted and cleaned.

A separate compression device is provided for each brush. The pressure is obtained by a spring-loaded plunger working in a barrel, all moving parts thus being enclosed. Means are provided for separately adjusting the pressure on individual brushes, and the gear is so designed that it is possible to remove and replace any brush without alteration of the compression adjustment. To minimize the damage that might result from a flash-over due to a particularly severe short-circuit, all machines having a D.C. voltage of 400 volts or above are provided with flash guards, which form a complete protection to the brush-adjusting gear and pigtails. These flash guards are hinged so that they can be turned back and locked open

to facilitate access to the brushes. All these advantageous features are clearly shown in Fig. 85.

The brush brackets are of cast iron with a separate brass box for each brush. The entire brush gear is of exceptionally robust construction, and is rigidly supported.

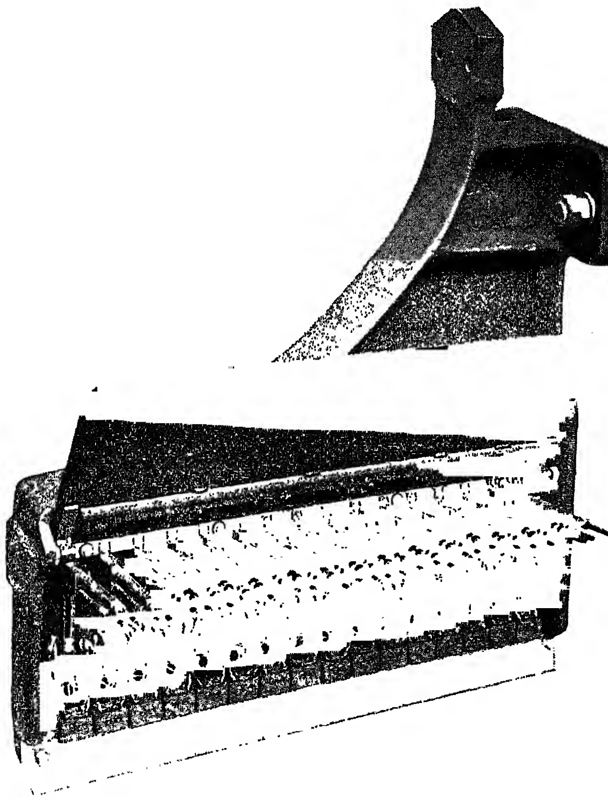


FIG. 85.—Brush Gear by the British Thomson-Houston Co.

It can be rotated for adjustment of the brush position, which, however, need not be changed after having been once set. The brush yoke, bus-rings, etc., are split on the horizontal diameter, so that the whole of the gear may be removed and replaced without upsetting the brush spacing.

There is another advantage in using this type of brush gear with one brush in front of the other. Fig. 86 shows one commutator with one brush per box, and another with two, one behind the other, and in the sketch it is assumed that the brushes in both cases are only making contact with the commutator at one spot due to imperfect bedding, or a rough part on the commutator. In the first case the area of commutation is merely that due to the point A, but in the second case is that between points A and B. Again, if there is a rough point on the commutator, this may cause the brush to be raised off the commutator, and

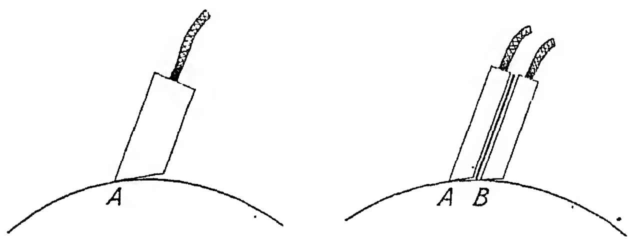


FIG. 86.—Sketch showing the advantage of using two Brushes, one behind the other, instead of one Brush of twice the thickness.

it will break circuit at A, whereas in the second case, if A is off the commutator, B will still remain on. It can readily be seen, therefore, that with imperfect bedding or a roughened commutator, the commutation is very much better in the second case than in the first.

The author has had a large machine running for over three years with this type of brush gear, and the results obtained have been far superior to any other type of gear in his experience.

Brushes. In December 1918, Mr. P. Hunter-Brown read a paper on Carbon Brushes before the Institution of Electrical Engineers, and it is to him and his paper that I am indebted for the greater part of the information which follows.

The contact drop of a copper gauze brush is stated to be about 0·2 volts. The drop on a carbon brush is about four or five times this figure, and from an efficiency point

of view this is a disadvantage. On the other hand, this larger contact drop is a very great advantage from the point of view of commutation, as it helps to prevent the flow of large circulating currents which would otherwise come into being, due to the difference of potential between one segment and another. It is this feature which renders it possible to obtain absolutely sparkless commutation, a condition which seldom existed with the copper gauze brush.

This voltage drop at the contact does not vary proportionally with the current, but remains remarkably constant over a wide range. It also remains constant for a variation of say 2,000 to 5,000 feet in the peripheral speed of the commutator, but above 5,000 feet it rises slightly.

The specific resistance of carbon is very much greater than that of copper gauze, and one would think that the loss here would be considerable, but in practice it is found that the loss from this cause is only about 10 per cent. to 15 per cent. of the loss caused by friction and contact resistance.

Friction. A low coefficient of friction is a matter of vital importance, especially with the high peripheral speeds now in use, as if the friction is high it may lead to chattering, and this is liable to cause chipping and breakage of flexible conductors. The coefficient of friction falls with an increase of speed, and it is suggested that this is due to a film of air between the brush and collector. This fall is so considerable that the *total friction loss* on a commutator with 40 amps. per sq. inch passing through a pure graphite brush is actually greater at a peripheral speed of 2,000 feet per minute than at a speed of 7,500 feet per minute.

Abrasiveness. This is the property possessed by a brush of scouring the commutator and thus keeping the surface clean; it is also of service in wearing down the mica at the same rate as the copper, and thus keeping a perfect cylinder. This is not of such importance nowadays, as in nearly all modern machines the mica is cut back so as to be always below the copper. The abrasive action

of the majority of brushes is very small indeed, but in some cases the action is of great service.

The author recalls a case of a rotary converter which would not give its full load without injurious sparking, and after trying various grades of brushes, a type was put on in which 1 or 2 per cent. of abrasive had been added. The effect was extraordinary, the machine giving its full load without any appreciable sparking, and it has continued to do so for the past fifteen years.

Hardness. This is quite distinct from abrasiveness. By " hardness " is meant the degree to which the material resists permanent deformation. This property is useful in limiting the wear of the brush itself.

The author has had experience of some brushes which gave perfect commutation, but were so soft that the brush required renewal in a few months. A harder brush was substituted, which, while still giving perfect commutation, has a wear of only about $\frac{1}{8}$ inch in a year. This is ideal from the station engineer's point of view, but the brush manufacturer's feelings would be somewhat mixed, as although he was giving great satisfaction to his customer, repeat orders would be few and far between.

The High-Speed Circuit Breaker

The high-speed circuit-breaker may be described as a specialized type of contactor as it is held closed by the current. It consists of a horseshoe-shaped magnetic circuit energized by a short coil (holding coil). This attracts and holds an armature heavily spring biassed to the open position attached to a contact arm which, when it moves, completes the main circuit of the breaker. In the gap of the horseshoe a bucking bar is assembled, and this bar carries the main current or a portion thereof.

The magnetic flux produced by the bucking bar will on heavy overloads so deflect the flux of the holding coil that the heavy springs attached to the armature are able to pull the armature to the open position and the circuit-breaker will interrupt the current. This deflection of the flux is practically instantaneous, as it only means that

the lines of force emanating from the holding coil which normally embrace the armature and hold it in the closed position, are drawn in towards the magnet, thus missing the armature—the number of lines of force passing through the holding coil itself remain practically the same.

In order to extinguish the arc effectively and rapidly when the breaker opens the magnetic blow-out principle is employed and the arc-chute construction is such that the contacts of the breaker are between the poles of the

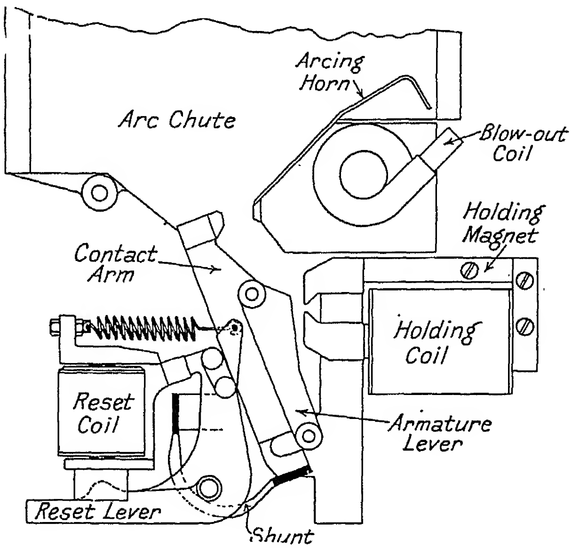


FIG. 87.—High-speed Circuit-Breaker. View showing the chief working parts.

blow-out magnet and directly underneath the arc-chute. The blow-out magnet is excited by series blow-out coils designed to give an intense field of small area around the main contacts. When the contacts begin to part the flux, set up by the blow-out magnet, forces the arc up into the long narrow slots in the chute when the arc quickly cools and collapses, thus opening the circuit. The arcing spaces are materially narrower than the contact tips, thus increasing the resistance of the arc stream for a given length and giving the maximum cooling effect to the vapours.

The arc chute is hinged at one end so that it may be swung back to facilitate inspection of the contact-tips.

The closing mechanism is arranged on the trip-free principle, that is to say, when the breaker is closing the

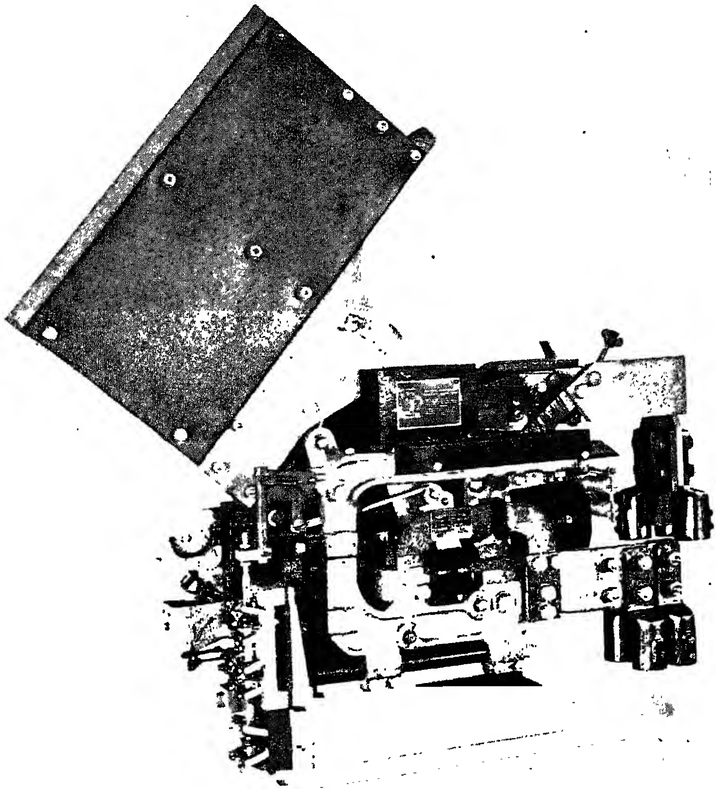


FIG. 88.—High-speed Circuit-Breaker. General View showing Arc Chute raised.

main contacts are not allowed to touch until the operating parts which brought the magnet armature into contact with the holding magnet have returned to the "open" position as affected by the de-energizing of the closing coil (or the return of the manually-operated link to the

"off" position). Thus the breaker is free to open immediately, if, when the contacts close, a heavy overload or short-circuit exists. This closing can be done either manually or by a special closing coil, which can be operated electrically from any distance.

Its Value in Protecting Machines. The high-speed circuit-breaker is a very valuable piece of apparatus, which is only just coming into use to any extent in this country. The flashing over of rotary converters and generators is a matter of some importance, as the damage that can be done to a machine if the circuit is not rapidly broken is sometimes serious. If a circuit-breaker can interrupt the current within the time necessary for a commutator segment to pass from one brush-holder arm to the next, an arc will not be drawn out and the machine will not flash over. This time, in the case of a 50-period machine, is about 1/100th of a second, and it is impossible to attain this speed of break in the ordinary type of circuit-breaker where it is necessary to knock away a catch or toggle mechanism before the breaker will come out.

In the specialized breaker which has been described electro-magnetic release is employed without any mechanical device at all, and on a short-circuit the total time elapsing from the first rise of current to complete interruption varies from ·008 to ·015 of a second. The time required to open an ordinary circuit-breaker under the same conditions would be from ·15 to ·5 of a second.

Another great advantage of this type of circuit-breaker is its power of discriminating between overload and short-circuit. If an overload comes on a feeder for a short time, due say to several heavy machines starting up at the same time, we do not want the feeder to trip out; but if there is a short-circuit in the feeder or its distributors the sooner the circuit is broken the better. Fig. 89 shows diagrammatically how this discrimination is accomplished by putting an inductive shunt in parallel with the tripping coil. R, R_1 and R_2 represent the ohmic resistance of the external circuit and two coils respectively, and L, L_1 and L_2 their inductance, and the diagram is drawn to roughly

illustrate the relative values of the ohmic resistance and the reluctance in the tripping coil and its inductive shunt. If the current is increased gradually it divides itself in inverse proportion to the ohmic resistance of those paths, and the circuit-breaker is calibrated for over-load with a slowly increasing current. If, however, a short-circuit occurs, the rate of increase of current is so great that the current divides itself inversely as the inductance and not as the resistance, with the result that the greater part of the current flows through the tripping coil.

This effect, combined with the speed of break of the circuit-breaker, brings about the curious result that when

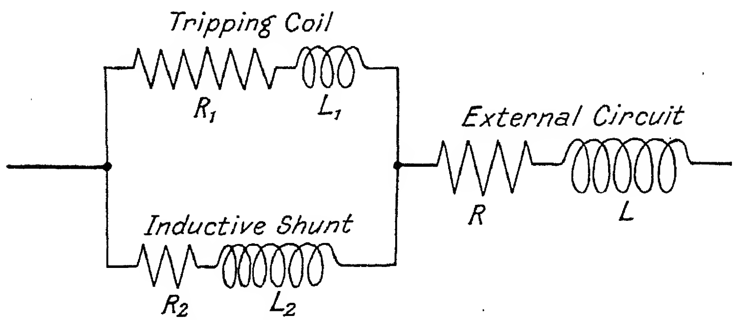


FIG. 89.—High-speed Circuit Breaker. Diagram to illustrate how it discriminates between a Short-Circuit and an Overload.

a short-circuit occurs the breaker ruptures the circuit before the current has reached the figure at which it is set to open with a slowly increasing current.

This is a very great advantage; firstly, because the current interrupted by the breaker is not large and the effect on the breaker is negligible; and, secondly, because it prevents the L.T. system from being subjected to severe current rushes which produce surges and cause other breakdowns. An objection that may be raised to this type of breaker, where to maintain contact a shunt circuit must be continuously supplied with pressure, is that it will tend to open circuit if there is a momentary drop of pressure on the supply. The author has witnessed an experiment on this point in which the holding-on coil was

short-circuited to imitate the condition resultant upon a drop of pressure in the supply. A period of fully one second elapsed before the breaker came out, this being due to the fact that the magnetism takes some time to die away unless some demagnetizing force is applied to it. This period of one second should be sufficient to prevent the breaker opening circuit when there is a momentary drop on the supply pressure.

End Play Device

This is a very simple but very efficient device, which can be applied to rotary converters, motor converters, or motor generators. Its object is to give the armature a slight reciprocating motion in a direction parallel with the shaft.

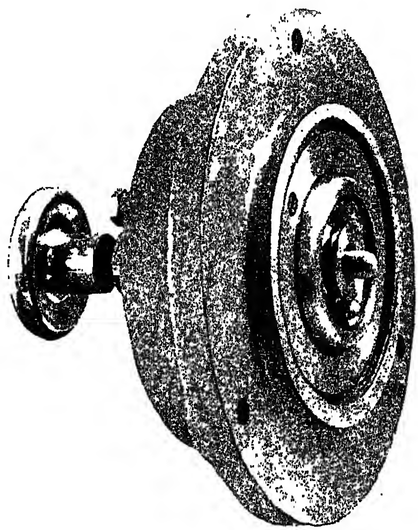


Fig. 90.—End Play Device.

The end play device is illustrated in Fig. 90, and consists of a steel plate set slightly out of parallel with the end of the shaft, the top being inclined towards the latter. The plate is grooved on the surface next to the shaft, and in the groove travels a steel ball. When the shaft rotates, the ball is carried up between the end of the shaft and the grooved plate, and, due to the inclination of the plate, forces the armature lengthways against the magnetic pull of the field.

When the ball has reached its top position in the groove, the armature, owing to its inertia, tends to move still further, with the result that the ball is released and immediately drops to its old position. It is then ready

to recommence the cycle of operations as soon as the shaft, drawn by the magnetic pull, returns to its old position. By this means, periodic end play is given to the armature.

This end play is beneficial in several ways. Firstly, as regards the bearings, it distributes the oil over the shaft, and the end-way movement keeps it smooth and prevents grooving. Secondly, it prevents grooving and cutting on the commutator, produces a beautiful surface on both brush and commutator, and improves the commutation. Thirdly, it does away with the difficulty with regard to the width of the slip-ring brush, and the slip ring on which it runs. If the machine is not fitted with this end-play device, and the brush is not so wide as the ring, it will form a definite groove in the ring; and, on the other hand, if the brush is made wider than the ring it will become grooved, and after a time the thin pieces at the edge will be broken off, and may fall in such a way as to cause a short-circuit.

With the end-play device, the brush can be made the same width as the ring, and no groove will be formed either on the ring or the brush.

The author's experience over a good many years with a number of machines, some with and some without this end-play device, confirms all the advantages mentioned above. It should be borne in mind that this device cannot be fitted to machines with roller or ball bearings.

Speed Limit Device

With modern machines, this device is considered as absolutely essential, and the apparatus is so simple and efficient that it would be foolish not to fit it.

When the A.C. switch on a rotary converter or motor converter trips out from any cause, and does not bring out with it the D.C. breakers, the machine will continue to run from the D.C. side, and will generally tend to attain a speed very much higher than the normal.

When this occurs, a weight, which is attached to the end of the shaft by a strong spring, flies out by centrifugal force, and when the speed reaches about 15 per cent.

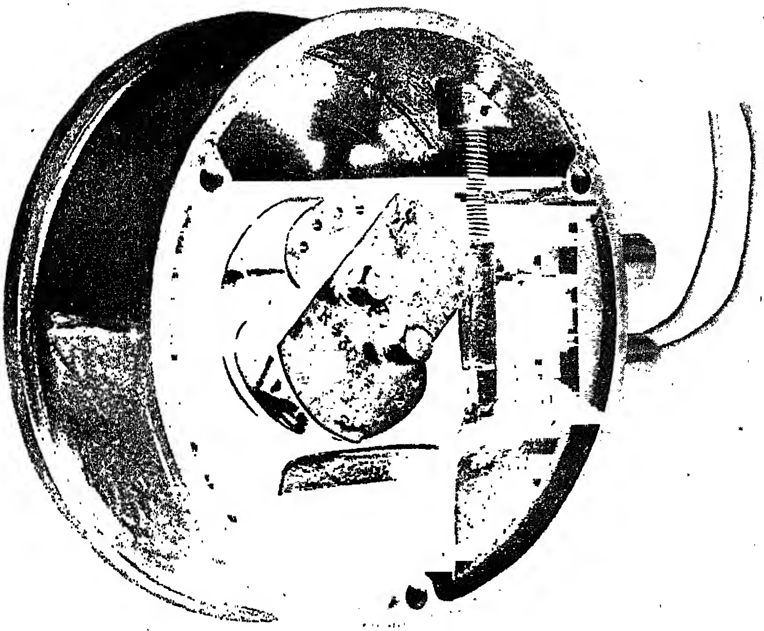


FIG. 91.—Speed Limit Device.

above normal, it knocks away a steel arm from its spring support, and causes it to fall and join two contacts which complete the local circuit through a trip coil on the D.C. breakers which then trip, thus cutting off all supply. This device is illustrated in Fig. 91.

CHAPTER XVI

CONTINUITY OF SUPPLY

Continuity of supply is the goal of every supply company, and the means by which it can best be attained is worthy of discussion. The supply company is the servant of the public, and it renders to that public a very vital service in the supply of current for lighting, heating and power. In these days, when, owing to the cost of building sites, the number of basements in a building is increasing, a cessation of supply is a serious thing, and the inconvenience and danger to the occupants when the light and power fail is very considerable. Again, the loss to the company in money and prestige due to a stoppage of, say, two hours, is very considerable, and in the case of a large London company, runs into several thousands of pounds.

Tests of Plant. The first essential is that all the plant, machines, mains and switchboards shall be the very best obtainable, and that they shall be tested to withstand the strain they will have to undergo in practice. What was good enough in the old days when the load was light, and the sets at the generating station and also the mains were small, is of no use under present conditions. The enormous output of modern generating sets, the increase in the size and number of cables, and the very much greater load, introduce problems when short-circuits occur, which did not arise before.

Every machine, whether it be a generating set or a converting set, which is installed in a large supply company's station, is liable to very heavy short-circuits and overloads, and in the author's opinion tests should be made at the manufacturers' works, to see that these machines will

stand the short-circuits and overloads without injury, and the short-circuits should be put on not once but several times. Such tests are specified in the case of converters which are to give supply to electric railways; and although it must be granted that the chance of a short-circuit in railway work is much greater than in ordinary supply work, still these short-circuits will occur and the machines must stand them. These tests, therefore, should be applied to all machines. Protective devices which have been thoroughly tried out must, of course, also be employed; but there is a tendency nowadays, owing to the multiplicity of designs, to put in too many of these devices, with the result that the machine is sometimes cut out, causing a drop of pressure or cessation of supply, when it is not necessary, and when, by leaving out one or more of these devices, continuity of supply would have been maintained. The machine, under these circumstances, may be subjected to very severe strains; but the correct thing to do is to build your machine so that it will stand the usage, rather than put in a protective device which will cut it out, and thus prevent the strain being put upon it.

Similar tests should also be applied to circuit-breakers, and in the case of cables it should be assumed that severe surges will occur, and the pressure test to which the cable is subjected should take into account the possible pressure rise.

Having discussed the tests to which the plant shall be subjected, let us now consider what precautions are necessary after the machines and cables are installed and laid. Faults will occur in the generating station, on the E.H.T. mains, in the substations, on the L.T. mains and on consumers' premises.

Consumers' Faults. Taking the faults in consumers' premises, in the general public interest, no fault on a consumer's wiring should be allowed to affect other consumers, except, of course, for the momentary drop when the short comes on. The smaller consumers are not likely to cause trouble, as the cross-section of their

installation mains will limit the current, and the ordinary fuses should clear the fault, without causing any fuses or circuit-breakers on the mains or in the stations to come out. The following remarks apply to large consumers, whose maximum load is so high that if fuses are used they will have to be of such large section that on a short they will not clear without bringing down other consumers.

No consumer has the right to object to the installation of apparatus controlling his supply which shall cut him off immediately a short-circuit occurs on his installation. How is one to accomplish this without penalizing the consumer by bringing him out when a very heavy overload comes on? We do not want a consumer to be cut off when he overloads his plant for a short time; the machines must be constructed to stand this overload without damage, and the mains should do so without any difficulty. The solution would seem to be the high-speed circuit-breaker arranged to discriminate between a heavy overload which comes on more or less gradually, and a short-circuit in which the growth of current is exceedingly rapid. Such an apparatus is on the market, and is described on pages 186–191. With this arrangement, a consumer might have a heavy overload on for some minutes due, say, to three or four printing machines starting up together, without being cut off. This overload would do no harm to machines or mains if it were not kept on for long; but if it persisted, some device on the consumer's switchboard should be arranged to cut off the load.

L.T. Mains Faults. Coming now to the faults on mains, modern practice is to put, in each feeder circuit, breakers with or without time lag, and to insert fuses at the points where the distributors which radiate from the feeders are connected on to a neighbouring feeder area. Difficulties arise in this system owing to the time lag on the fuses, and in many cases the circuit-breakers at the station and on the feeders come out before the fuses have blown, and therefore a fault on one feeder section is

liable to bring out another section or sections. The obvious solution that occurs is to make the circuit-breakers have sufficient time lag to ensure that the fuses shall blow. The author's experiments with heavy-current fuses do not lead him to favour this idea, as the time lag on the circuit-breakers would have to be several seconds, and the damage done to mains and machines during those seconds, if a dead short-circuit is kept on, is too serious to contemplate with equanimity.

If it is borne in mind that the ratio between the current which may be allowed to pass in a fuse continuously (say 200 amps.), and the current necessary to cause that fuse to break circuit in half a second is about 1 : 10, it will be seen that as several fuses are in parallel, and have to be blown to clear the feeder section, the circuit-breaker at the station end of the feeder would have to be set at an impossible figure, if it were to remain in until the fuses blew. The way out of the difficulty, although it may be costly, is to put circuit-breakers in place of the fuses in the distributors. These circuit-breakers would be set to go at such a current that the sum of all the current settings of the breakers surrounding a given feeder point was somewhat less than the setting on the breakers in the feeder itself.

Another safeguard would be to make these circuit-breakers in the distributors of the higher speed type, leaving the circuit-breakers in the feeders at the substation of the ordinary type. These distributor breakers would then be bound to act with certainty before the station breaker, and we should be introducing a beneficial time lag into the station breaker, without the disadvantage of increasing the time during which the short-circuit current is passing. This would do away with the objection to the time lag in station breakers previously put forward.

Provision should be made at the substations to enable any feeder to be isolated on to a separate machine, so that in the event of a heavy earth coming on, the feeder area on which the earth is, could be separated from

the rest of the district, and if the earth developed into a short-circuit, only the bad feeder area would be affected.

Substation Faults.

Switchgear. The faults likely to occur here are on the switchgear, transformers and machines. In another part of this book the development of the E.H.T. busbar is dealt with, and for our present purpose we have only to consider the survival of the fittest. In the author's opinion, the completely enclosed ironclad type is the best ; but as it is not always possible to utilize this right throughout the substation, the stone cubicle with separate chamber for each phase has to be employed. The trunk main busbars should undoubtedly be of the completely enclosed ironclad type, and the oil switches controlling the trunks must be capable of interrupting the circuit on the supposition that a dead short-circuit occurs in the substation, and that the whole of the plant likely to be running at the generating station is providing current on this short-circuit. This calls for very sound construction and ample size in the tanks containing the oil, and these switches should be tested as nearly as possible under the conditions in which they have to work.

Transformers. Whether they are used for supplying an alternating current, L.T. or E.H.T. network, or are working in conjunction with rotary converters or rectifiers, transformers should be of the single-phase type, and a spare should be provided which can be wheeled into place, and thus facilitate the resumption of supply by the transformers.

The Protective Devices. Those used in connection with transformers and machines are so numerous and so ingenious that there is a temptation to put in one of every type of these devices, to ensure that, whatever happens, the transformer or machine shall be protected. In the author's opinion this is a mistake. As before stated, the plant must be capable of standing anything

to which it is likely to be subjected, including a large overload for a reasonable time, and what we should aim at is to instal devices which will not immediately cut out the plant when a heavy overload is thrown on to it, due to the failure of other plant; but, on the other hand, if the plant itself is faulty, this device must cut it out at once. When a machine or transformer fails, if continuity of supply is to be maintained, we want the rest of the plant to hang on, and only be cut out when by being left on circuit it will be seriously damaged.

Leakage protection or balanced protection must be installed to protect the transformer or machine from internal faults, as it is obviously no use attempting to keep the plant in commission if it is faulty. Reverse current relays, however, are to be avoided, especially in those substations where storage batteries are installed. The reason for this is, that if the reverse current relays are set to trip when the reverse current has reached a comparatively low figure—this is the usual practice—any slight drop on the E.H.T. side will cause the batteries to push current into the D.C. side of the converter sets, causing them to trip out just when they are most required. This tripping out of the rotary converters installed in the substations controlled by the author became so serious that the whole of these reverse current relays were disconnected, and have not been used since. An overload relay of some kind must be provided, as otherwise the plant might be seriously damaged; but the overload should be set at a very high figure, say three or four times full load.

Temperature Relay Trip. The best device of all for tripping the machine out is the machine temperature relay. In this case the ultimate deciding factor as to whether the machine shall be cut out or not is the temperature of the machine itself. A current transformer on one of the supply phases energizes the primary of a current transformer in the relay. The secondary of the relay heats up a thermal strip, which possesses a heating characteristic similar to that of the machine, and thus

opens the tripping circuit before the temperature in the machine has risen to a dangerous value. This device, while protecting the machine from damage, ensures that it shall be kept in circuit till the last possible moment, and thus tends to maintain supply.

E.H.T. Trunk Mains. The system should be of the interconnected or ring main type, so that the failure of any one cable will not deprive a substation of its supply. It is of vital importance that the failure of one cable shall not affect any of the others, and a great deal of trouble has been experienced with protective systems in the past on this score. A considerable number of very excellent protective systems have been evolved, but the one which the author has had experience with, and which guards against the danger mentioned above, is the Merz Price two-core pilot voltage balance protective system, with diverter relay. This, operated with current only, gives complete fault protection with a two-core pilot. It can be set to work at low-fault currents, and has complete stability with straight-through currents up to 10,000 amps. without the use of compensated pilots. The straight-through currents referred to are those feeding a fault in another cable, and the device takes no account of this current, and therefore does not trip out a healthy cable.

Generating Station Faults. The remarks made on substation faults apply equally in this case, and, in fact, from the point of view of continuity of supply, it is even more important that a generating set shall not trip out until the last moment.

The size of generating units is becoming greater than ever, and in many stations the load during the daytime for quite a considerable part of the year does not warrant the running of more than one machine. It is of the utmost importance, therefore, that this machine shall hang on to the load unless it is faulty, as otherwise the whole of the system which it supplies will be down.

The practice of putting reactance coils between sections of the busbars, in the machine circuits and also in the

feeders, is increasing, and by reducing the current that flows to a short, increases the stability of supply.

The switches on the trunk mains must be of very high breaking capacity, so as to make sure that faults will be cleared.

Summary. Summarizing the suggestions in this chapter, the author is of the opinion that continuity of supply is best ensured by the following precautions :

Generating Station. Reactance coils, either between sections of busbars, in generator circuits, or in feeders, or combinations of these arrangements. Compound filled, ironclad E.H.T. switchgear, capable of breaking circuit on the heaviest short. Generators, fitted with leakage or balanced protection to cut out the machine at once if an internal fault occurs, otherwise the machine to rely upon thermostatic relay cutting it out when getting overheated. No ordinary current overload to be fitted.

Trunk Mains. Ring main system with protective system on each cable, not subject to coming out with straight-through current. Merz Price two-core pilot voltage balance with diverter relay preferred.

Substation. Single-phase transformers in static substations and in other stations where rotaries are used. Leakage or balanced protection on transformers, rotaries, and other converting plant. No reverse current relays and overload relays only if set at four times normal full load, but machines cut out by thermostatic overheating relay. High breaking capacity ironclad E.H.T. switches on trunks, and controlling E.H.T. busbars.

L.T. Mains. Circuit-breakers on each feeder, single-feeder areas connected to neighbouring areas through circuit-breakers in street boxes. Provision at substations for isolating faulty areas on separate machines.

Consumers' Faults. All large consumers to be connected through circuit-breakers, and in the case of D.C. supply, these to be of the high-speed discriminating type, *i.e.* will stand heavy overload for a short time, and will come out at once on a short-circuit.

Continuity of Supply in the Future. In the foregoing remarks, the author has given what in his opinion is necessary, in order to maintain continuity of supply with the plant and apparatus mostly in use at the present time in this country, and in the following pages he proposes to look forward and see what may be possible in the future.

Automatic Substations. The enormous extension of the automatic principle applied to machines, switches and mains in recent years, and the success that has been attained, makes one wonder whether any limit can be set to the application of this principle. In America there are about 700 automatic stations working successfully, and in this country, although the number is very much less, the tendency is to increase very rapidly.

There seems to be no operation in connection with the starting up, stopping, and regulating of machines, the switching in and out of feeders and L.T. mains, that cannot be undertaken by automatic apparatus.

The most valuable feature about automatic gear in connection with continuity of supply is that it is always on duty watching for an opportunity to perform the function allotted to it. It is true that the apparatus is subject to certain diseases, such as bad contacts, faulty insulation, etc.; but the very small number of faults that occur in the apparatus in use at the present time leads one to hope that in the future these causes of trouble will be negligible. The best of switchboard attendants is liable to dine "not wisely but too well," and the consequent digestive troubles render him far less able to deal with an emergency which may arise than in the case of automatic control, when the apparatus is entirely free from such troubles.

Again, if a minor fault occurs which involves the cutting off of some consumers, it may not be possible for the switchboard attendant, with the apparatus installed, to know what has gone wrong and how to put it right, especially in the case of sections of the mains, away from the station, going dead. If the automatic principle is

fully applied, the very fact of something going wrong starts a train of operations, the object of which is to restore the supply.

It is stated that in Kansas City, the duration of interruptions which in the past, with manually-operated stations, have amounted to forty-five minutes to $1\frac{1}{2}$ hours, have been reduced with automatic operation to two minutes (*General Electric Review*, June, 1925, page 569). This is a very valuable improvement, as apart from the loss of revenue due to the consumer being off for $1\frac{1}{2}$ hours, there is the loss of prestige to the company and the serious inconvenience to the consumer.

For some years past, hydroelectric generating stations have been started up automatically; and although it is admitted that these are simpler than a steam turbine station, it might be possible to apply a partial application of the automatic principle to the latter.

Owing to the large size of individual units in a modern generating station, it often happens that for a considerable part of the year only one set is running, and if this shuts down the matter is serious, and the starting up of another set as quickly as possible is of vital importance. Would it not be possible for the cessation of supply to start a train of operations in connection with a stand-by set, with the object of reducing the time before that set could be delivering current, to a minimum?

Again, with E.H.T. mains, it not infrequently happens that a switch at one end of a cable comes out, but the one at the other end remains in. Under these circumstances there should be no harm in closing the switch that has opened, and this could be done quite easily automatically. Coming to the substation, if automatically controlled, the machines will be arranged to start up in a regular sequence which can be altered at will, and in the event of failure of one machine, another automatically takes its place.

With regard to the L.T. mains, it frequently happens that a short-circuit which is sufficient to pull out a circuit-breaker, clears itself, and therefore the system of auto-

matically reclosing circuit-breakers through a resistance should reduce the time of failure to a minimum, and it might be possible to apply the principle to sectional circuit-breakers in street boxes.

Supervisory Control. If to the purely automatic control, supervisory control is added, the possibilities of quick restoration of supply are increased greatly. Supervisory control has been applied to a considerable extent in America, particularly in connection with the E.H.T. systems of some of the huge combinations that exist there; but up to the present it has not been used much in connection with the L.T. supply. In a great number of undertakings supplying current in this country, and others which are being laid down, when a L.T. feeder is laid, a three-wire pilot cable is put in at the same time. The pilot cable terminates in the feeder box from which various distributors radiate, and is connected to the end of the feeder. At the station end it is connected to a voltmeter, recording or otherwise; but if we substitute for this voltmeter, resistances of different values, various currents can be caused to flow in the pilot cable. By installing in the feeder box relays, some working with one current and others with another current, some connected to the positive and some to the negative, a considerable number of operations can be controlled by these three wires. If now we make these relays open and close circuit-breakers controlling the radiating distributors, a considerable amount of control of the network is possible from the substations, and the restoration of supply is greatly facilitated.

These pilots can also be made to work indicating lamps, showing which breakers are in and which are out. Messrs. Bertram Thomas have introduced a system for the remote control of converting sets based upon this principle, and this has been working satisfactorily at Hull and Croydon.

Visualizing the future, one can picture the mains engineer when a breakdown has occurred on the network proceeding to a little office in the substation in which are

arranged push-buttons, switches and lamps connected to the pilots, and controlling the circuit-breakers in the street boxes. The lamps would show him which breakers were out and which were in, and by manipulating the push-buttons he could connect and disconnect his distributors at will.

The switching on of the distributors would be through a resistance, and if the short was on that particular circuit, the breaker would not close. If the feeder itself went dead, the relays could still be worked from the substation end by making suitable connections.

There is another point of considerable importance, which those who are responsible for the design and arrangement of the "grid" (the future source of supply to all authorized distributors), should bear in mind. The point is that all the large substations in important towns should, wherever possible, be provided with two more or less independent sources of supply. Let us take, for example, the area covered by the London Power Co. This company has been formed to take over the generating stations of, and supply power to, the nine constituent companies, namely London Electric Supply, Metropolitan, Charing Cross, Westminster, St. James's and Pall Mall, Kensington and Knightsbridge, Brompton and Kensington, Chelsea and Notting Hill.

Four only of the generating stations will be kept working, namely, Grove Road, Willesden, Bow, and Deptford. A new generating station is now being erected at Deptford West, and another one is projected at Battersea. Grove Road, Willesden, and Bow are at present running in parallel without reactances; but when the total plant in these stations has increased beyond a certain figure, reactances will be necessary between them. Reactances are installed between Deptford West and the above group of three, and also reactances will be connected between Battersea and Deptford, and Battersea and the group of three.

Into all the large existing substations and the generating stations which will be converted into substations, 22,000-

volt mains are run from two of the generating stations, or groups of generating stations, which are connected by reactance. Now it is obvious that these two sets of 22,000-volt busbars in the substations must not be joined together, as by so doing the reactances between the generating stations would be rendered useless.

We therefore have the condition that there are practically two sources of supply in each substation; and if one of these goes down, the other should remain alive. If one could be certain that the reactances between the generating stations would ensure that a fault on the system would not pull down the others, this system of divided busbars in large substations would be a very great asset from the point of view of continuity of supply. If, in addition, a battery of fairly large size, such as the author has had in use for the past twenty-five years, is installed, the chances of a complete cessation on the L.T. mains become very remote.

To illustrate this point, let us take a substation of, say, 10,000 kW. (a figure which is getting near the point at which it becomes uneconomical to distribute from one point), the plant consisting of four 2,500-kW. sets, arranged two on one E.H.T. busbar, and two on the other (see Fig. 92). During the greater part of the year, one of these 2,500-kW. sets will be running alone, and it is obvious that if for some reason, such as a faulty catch on circuit-breaker, or defective relay, this machine trips out, the division of the station into two sections is of no use in maintaining supply, and if no battery is floating on the line, every one connected to that substation will be in darkness or have their power cut off, and complaints will pour in. If, however, a battery is installed of such a size that it will maintain the load thrown off by the 2,500-kW. set, for, say fifteen or thirty minutes, the consumer will still have supply, although at reduced pressure.

In the author's experience, this tripping of the one machine running has happened on several occasions, and the battery has maintained the volts at 150 (normal

200) or over for the five or ten minutes necessary to get the machine back again, with the result that practically no complaints were received.

If we then take the next stage, and assume that the load requires two of the 2,500-kW. sets to be running, these will, of course, be run one on each of the two sections.

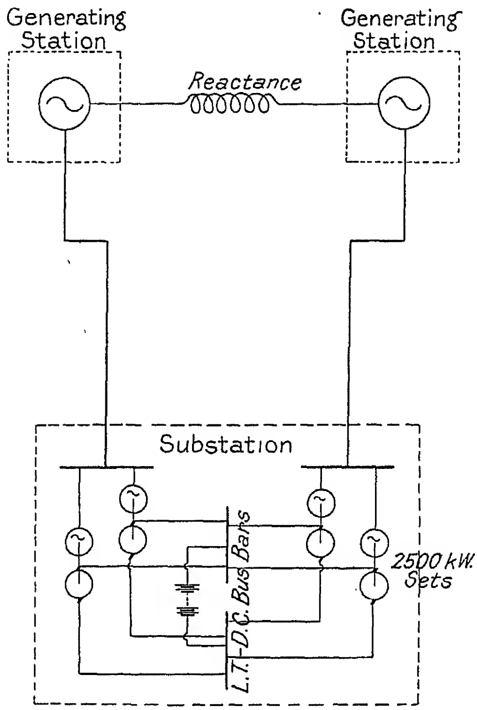


FIG. 92.—Continuity of Supply. Diagram to illustrate the advantage of having Supply from two Generating Stations.

If a machine trips out for any reason, or even if the E.H.T. supply fails completely on one section, the other machine will remain running, and the battery will take up the load of the machine that is lost. As these machines are specified to give 50 per cent. overload for fifteen minutes, the load on the battery will not be so great, and the pressure can probably be maintained at, say,

180 volts, until it is restored to normal by another set being put in.

The next stage is where three 2,500-kW. sets are necessary to deal with the load, and these will be two on one section and one on the other. If an individual machine trips out, or if the section which has one machine on it goes down, the remaining machines and the battery should maintain the pressure at practically normal. If, however, the section which has two machines on it goes dead, the condition will be rather severe, and the pressure may drop somewhat below 150 volts. A reasonable light will, however, be given to the consumer, and within five minutes the pressure should be restored.

The final stage is when the four 2,500-kW. sets are running, and here again if an individual set trips out, the pressure could be maintained at normal. If one section goes down, the two remaining machines with their 50 per cent. overload rating will take up the load of one set, and the battery will deal with the other, the pressure probably being kept up to about 170 volts.

From the above it is clear that if the system of two E.H.T. busbars in a substation is adopted, and a battery of suitable capacity is available, the supply to the consumer should be maintained under any conceivable set of circumstances, short of a complete burn-out of the substation, which with modern fireproof methods of building should be very unlikely.

The President of the Institution of Electrical Engineers, Mr. Archibald Page, in his inaugural address, makes the following statement: "As regards continuity of service, though we may be justly proud of the fact that our standard of excellence in this respect is unequalled throughout the world, to secure 99·9 per cent. of continuity, involves much greater capital expenditure than does, say, 99 per cent. While, therefore, in the business and shopping centres of large towns, nothing but the best is good enough, this policy need not be universally adopted. . . ."

Mr. Page agrees with the author that in London and

similar large cities or towns it is the 99·9 per cent. standard that we must aim at.

The author has dealt with this matter rather exhaustively, as he is, and always has been, a keen advocate of the importance of continuity of supply, and, although he quite agrees that capital expenditure to that end must not be carried to excess, he wishes to combat as far as he can the doctrine that reduction of generating costs is the most important thing to be considered.

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